Innovations in Science Education and Technology 19

Georgios Tsaparlis
Hannah Sevian *Editors*

Concepts of Matter in Science Education

Springer

Concepts of Matter in Science Education

INNOVATIONS IN SCIENCE EDUCATION AND TECHNOLOGY

Volume 19

Series Editor

Cohen, Karen C. *Weston, MA, USA*

About this Series

As technology rapidly matures and impacts on our ability to understand science as well as on the process of science education, this series focuses on in-depth treatment of topics related to our common goal: global improvement in science education. Each research-based book is written by and for researchers, faculty, teachers, students, and educational technologists. Diverse in content and scope, they reflect the increasingly interdisciplinary and multidisciplinary approaches required to effect change and improvement in teaching, policy, and practice and provide an understanding of the use and role of the technologies in bringing benefit globally to all.

For further volumes:
http://www.springer.com/series/6150

Georgios Tsaparlis • Hannah Sevian
Editors

Concepts of Matter in Science Education

Springer

Editors
Georgios Tsaparlis
Department of Chemistry
University of Ioannina
Ioannina, Greece

Hannah Sevian
Department of Chemistry
University of Massachusetts, Boston
MA, USA

ISSN 1873-1058 ISSN 2213-2236 (electronic)
ISBN 978-94-007-5913-8 ISBN 978-94-007-5914-5 (eBook)
DOI 10.1007/978-94-007-5914-5
Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2013940096

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Foreword

The use of the plural in the title of this book, *Concepts of Matter in Science Education*, acknowledges that matter is not a singular idea. ‘Solid, liquid, gas’ – this trio of words rolls easily off the tongue, sounding a bit like ‘animal, vegetable, mineral’, the party game where you have to work out, by clever indirect questioning, which is the category for some object members in turn choose.

Before we come to school, almost all of us have a sense of what is solid, what is liquid and that air is a gas. One might expect that this intuitive and experiential knowledge should be readily built on and developed through schooling, until all of us have gained the precise and rich meanings in particulate terms that the physical sciences now give to these states of matter, their transformations and their interactions.

If it were that simple, we would not be confronted with yet another book which, as much as it suggests new approaches to the teaching of these topics, confirms that they are still very difficult for students to learn.

One of my most vivid memories of observing school science teaching was the painful empathy I felt for an elementary school teacher carefully following the instructions from the Science Teacher’s Guide to communicate the distinctions and similarities between the three states of matter and their particulate nature. The teacher poured some water into a measuring beaker and then dropped some solid camphor balls into another beaker, both of which were to be left over the weekend to show the similar loss of matter through evaporation/sublimation, as an introduction to the particulate model in the subsequent lessons. When the students were asked to describe these two actions, they confirmed that both substances had been ‘poured’, whereupon the teacher insisted she had ‘poured’ the liquid and ‘dropped’ the solids. This was just the start of the totally confusing discourse that ensued over the next couple of lessons. In addition, the communication was not at all helped by the rather ethereal diamonds and ghostly circles that the textbook used to represent the subliming/evaporating gaseous state.

Visual representations or mental pictures are powerful adjuncts to give meaning to the words science teachers use to describe phenomena. The states of matter are further badly served by the diagrams most textbooks use to accompany statements like ‘solids have a fixed shape’, ‘liquids take up the shape of the containing vessel’ or 'gases are rapidly moving tiny particles'. In practice, powdered solids have flexible shapes like liquids, and it is a gas that really takes up the shape of its containing vessel. Furthermore, given the scale of the drawn gas particle, it would be a rare event to have even one molecule in the diagrammatic vessel. Alex Johnstone in Scotland once devoted three pages of his chemistry textbook to bent-shaped H–O–H symbols, with just one ionised as H^+ and OH^-, to impress how rare 10^{-7} is. Even so, he had to admit that all 150 pages of the text would be needed for an accurate representation.

Almost every set of words and diagrams science textbooks and teachers use to define and distinguish these three states of matter and their particulate nature turns out to be ultimately inadequate to deal with the varieties of matter we now have. It has always seemed ironical that the gaseous state, the least familiar to young persons and most recently recognised by scientists as other than contaminated air, is now in science the most readily associated with, and quantitatively described, in particulate terms.

I learnt in school many years ago about colloids and emulsions but was never sure what states they were. Are colloids in solution liquid or are they very small solid particles suspended in a solvent? The answer is *YES* and *YES*, depending on the substance that is in this colloidal state. Liquids like cream can be colloidal in homogenised milk, and gold particles can be colloidally suspended in a liquid. I also learnt that glass was a supercooled liquid, because it did not have a crystalline structure and because it does flow, albeit so slowly that it is only observed in the glass windows of very ancient buildings. But glaciers which also 'flowed' (and somewhat faster) were solids and not supercooled liquids, although they were cold. These ambiguities were just the harbingers of the new states of matter that became part of my adulthood – polymers, followed by plasma (electrically conducting gases?), and now the nano-state of matter with its almost atomically dimensioned substances in two or three dimensions. My awareness of this last state occurred when we were making very high surface nickel oxide for catalytic purposes and succeeded so well that our oxide particles did not contain enough ions for the alignment of their spins to generate the magnetic properties that nickel oxide usually displays.

In all these cases, the physical sciences have gone beyond the macroscopic nature of these three states of matter and a simple particulate model to explain their properties and interactions. Plasmas are now part of everyday language because they are basic for a number of everyday technologies. Their conditions for existence make them neither solid nor liquid, but their electrical conducting properties so distinguish them from gases that they have been defined as a new state of matter. The public media and the large sums of public money involved make us all aware of the use physicists make of accelerating beams of protons and other charged particles in synchrotrons and the super accelerator at CERN. How do physics teachers describe these beams and the products of their collisions as particles of matter? If the Higgs boson has been discovered as the missing fundamental particle of the standard theory of matter, it has a mass very much higher than that of the subatomic particles – protons, neutrons and electrons. Nevertheless, it is this trio of particles that chemistry teachers teach to their students as the distinguishing components of the structure of elementary matter, and as the keys to the variety of ways, these elements bond together to form a myriad of other substances and to the radioactive behaviour of some of them.

The physical sciences have a proud history of finding ways to measure all sorts of things. When it comes to the states of matter, several SI units are invoked. The mass of a solid substance is expressed in terms of the kg, the amount of a liquid can be in kg or in cubic decimetres (but not in the everyday litre, since it is not an SI unit), and the amount of gas in kg or in cubic decimeters, with the temperature and pressure, is also specified. None of these measures, however, imply anything other than continuous substance, and this was not good enough for chemists who fought hard for a measure that specifically refers to the particulate nature of matter. Finally, the mole was introduced and received SI status as the unit of amount of substance or matter. The difficulties that this means of measuring matter has raised for chemical educators are indicated by the fact that texts, teachers and students still continue to refer to 'the concept of the mole', when they should be referring to the concept of amount of substance.

The sciences would not be science without the concepts that have been invented to describe and explain aspects of matter. But, defining and expressing those concepts in crisp distinctive words and actual or mental pictures and models is not easy. The big ideas in science that explain conceptual relationships in a field develop slowly, and only emerge when enough different phenomena are recognised as having some aspects that are common. The particulate nature of matter, like a number of other big ideas in the sciences, is a powerful but abstract set of ideas that we now try to introduce to students at school before they have had anything like enough experience of the phenomena to which it applies. Those of us who somehow succeed to get further into the experiences of science probably had the same problems, but, retrospectively, we know the big ideas make sense and are useful, despite the obvious and ongoing difficulties their ambiguous and confusing definitions raise for each new generation of science students. Such short-cutting did not happen in science, and it is unlikely to be achieved easily in science education.

From the initial studies of students' misconceptions and alternative conceptions in the 1980s, we know that 'states of matter' and 'the particulate model of matter' have been two very poorly understood key topics. Since then, there has been much research on these topics in many countries, and a number of new teaching approaches have been tried to remedy these outcomes. The emergence of another very substantial book covering a further number of approaches to both the research and teaching about 'matter' is both a source of encouragement and despair. I am encouraged by the positive note that underpins the innovative nature and novelty of the approaches now being reported. I despair that such abstract macroscopic and microscopic notions in science are still largely being directly transmitted as definitions in science education, rather than emerging as the culmination of experiencing many of the relevant natural phenomena, including ones that involve those exciting new forms of matter that are not yet even on the horizon of our school science agenda.

Emeritus Professor, Monash University Peter J. Fensham
Melbourne, Australia
Adjunct Professor, Queensland University of Technology
Brisbane, Australia

Editors' Acknowledgements

Most of the chapters in this volume were contributed by individuals who presented at a symposium entitled 'Particulate and Structural Concepts of Matter', held at the University of Athens, in Greece, on November 5–8, 2010, and organized by Georgios Tsaparlis and George Kalkanis. At the conclusion of the symposium, the participants responded positively to the expressed desire by Georgios Tsaparlis to develop from the symposium an edited volume of papers, subsequently organized and edited by Georgios Tsaparlis and Hannah Sevian. Most of the presenters included co-authors on their papers who were not present at the symposium. Not all symposium presenters contributed manuscripts. In addition, several additional papers were solicited by the editors of the volume in order to create a more complete collection of papers.

The editors are grateful for the commitment of all of the authors to this volume in persisting through several revisions, both after internal and external reviews and the editors' reviews. Each manuscript was single-blind reviewed between one and three times, both by an author internal to the book and an external reviewer, and every manuscript was taken by its authors through at least three revisions. External reviewers were selected on the basis of their expertise on the reviewed manuscripts. In the case of the two editors' papers, the review processes were handled confidentially by the other editor. The editors thank the internal authors who reviewed as well as those who served as external reviewers for their expert and constructive feedback that contributed greatly to the improvement of the manuscripts. The editors are also very grateful to Professor Emeritus Peter Fensham for the Foreword he contributed to the volume.

Georgios is grateful to all authors who participated at their own expense in the Athens symposium, making possible its realisation and hence the realisation of this book. He also thanks the authors of the additional papers. He dedicates his work to his wife, Gioula, to his son, Iason, and to his daughter, Vasia. Hannah appreciates the careful help contributed by one of her graduate students, Steven Cullipher, who assisted with some of the editing tasks and organisation of files for the publisher.

She dedicates her work on this volume to her children – Terra, Anahid and Siroun – and to her husband, Peter Johnson, who exhibited immense patience for the long hours of editing devoted to bringing this book to light.

University of Ioannina, Greece Georgios Tsaparlis
University of Massachusetts, Boston Hannah Sevian

Contents

About the Contributors

Karina Adbo is a lecturer in science didactics at Linnæus University, Kalmar, Sweden. She obtained both her M.Sc. degree in chemistry and her formal qualification as an upper secondary school teacher of chemistry and biology from the University of Kalmar in 1999. After several years of university teaching and research in the field of molecular imprinting science and technology, she commenced Ph.D. studies in chemistry didactics. She was awarded her Ph.D. in 2012 by Linnæus University. Her research is focused upon teaching models in chemistry education.

Sevil Akaygun is an Assistant Professor of chemical education in the Department of Secondary School Science and Mathematics Education at Boğaziçi University, Istanbul, Turkey. She earned her Ph.D. from University of Northern Colorado in 2009, investigating the effects of dynamic computer visualisations on students' mental models. She taught high school chemistry and middle school science for 12 years before moving to the field of teacher education. Her research interests include dynamic computer visualisations, chemistry teacher education and nanoscience education.

George Bodner is the Arthur E. Kelly distinguished Professor of chemistry, education and engineering at Purdue University. He was one of the founders of the Division of Chemical Education at Purdue that has graduated more than 75 Ph.D.'s in chemical education. He was also one of the inaugural members of the School of Engineering Education at that institution. He is a Fellow of both the American Chemical Society and the Royal Society of Chemistry. This year, he is both the chair of the ACS Division of Chemical Education and a member of the ACS Board of Directors.

Astrid M.W. Bulte is an Associate Professor at the Freudenthal Institute for Science and Mathematics Education at Utrecht University. She focuses her research on two issues: design-based research of context-concept approaches using authentic practices and professional development of teachers. She holds an M.Sc. and a Ph.D. in chemical engineering science (both from the University of Twente, the Netherlands). She has teacher degrees in chemistry and the Science of Public Understanding and has taught chemistry and physics in secondary school for 5 years. In her current position, she teaches communication skills in the undergraduate chemistry programme and contributes to teacher education. She is a curriculum advisor for the development of science programmes for secondary and university education.

A.L. Chandrasegaran is a postdoctoral researcher at the Science and Mathematics Education Centre, Curtin University, Australia. He holds a B.Sc. (Hons) (Canterbury, NZ), M.Sc. (ScEd) (Curtin), Ph.D. (Curtin) and a Teachers' College Diploma (Christchurch, NZ). For most of his career, he has taught secondary school chemistry in Malaysia, Singapore and Perth, including 12 years serving as the principal of a large secondary school in Johor, Malaysia. His research interests focus on chemistry education at both secondary and early university levels, and his work is published in several leading journals.

Mei-Hung Chiu is a Professor in the Graduate Institute of Science Education at the National Taiwan Normal University, Taipei, Taiwan. She earned her Ed.D. from Harvard University in 1990 where her main area of interest involved investigating students' learning in science via the use of microcomputer-based laboratories (MBL). Her research about students' science understanding, mental models in science learning and student and teacher conceptual change has been published in numerous international journals. Currently, she chairs the International Union of Pure and Applied Chemistry (IUPAC) Committee on Chemistry Education and serves as associate editor for the Journal of Research in Science Teaching.

Shiao-Lan Chung is a Ph.D. student at National Taiwan Normal University. Her research interests include development of diagnostic instruments to determine students' understanding and conceptual change in science and the use of multi-representational models in chemistry. She obtained her B.S. in chemistry and her M.Sc. in science education from National Taiwan Normal University. She has 17 years' experience working as a high school chemistry teacher.

Gregory Durland is a high school chemistry teacher at Wilson High School in West Lawn, Pennsylvania. He is also a chemical education graduate student at Purdue University. His research includes investigating pre-service elementary teachers' understandings of basic chemistry concepts and their beliefs about teaching these concepts.

Ingo Eilks is a Professor of chemistry education in the Institute of Science Education (IDN) at the University of Bremen, Germany. He earned his Ph.D. in 1997 with experimental works on modern catalysis in chemistry education. Today his working areas are – among others – socio-scientific issues-based science education, the particulate nature of matter, cooperative learning in chemistry education, education for sustainable development (ESD) and research on science (student) teachers' beliefs and pedagogical content knowledge (PCK).

Victoria Fox studied cognitive psychology as an undergraduate at Clark University in Worcester, MA, USA, where she completed an honours thesis on conceptual change within the areas of matter and conservation in the context of elementary school science education. She most recently served 2 years in the Peace Corps, as a rural community health volunteer in the West African nation of Benin. During her service she designed and implemented a research study to uncover cultural beliefs and practices affecting local malaria prevention efforts. She is currently pursuing a career in medicine.

Kathryn E. Frazier is a doctoral student in psychology at Clark University in Worcester, MA, USA. Her research interests centre around conceptual change in children and students in the context of science education. Recent projects involve conceptual change in early elementary school and children's understanding of matter, material and number. Additional research interests involve societal and feminist approaches to cultural discourses of gender, particularly as they relate to individual experiences of and meaning making around interpersonal violence.

Lilia Halim is Professor of Science Education in the Faculty of Education at the National University of Malaysia. She earned her Ph.D. in 1997, examining science teacher education programmes with an emphasis on the development of physics teachers' pedagogical content knowledge. She has conducted studies and published articles on the identification of science pre-service teachers' pedagogical content knowledge and ways to develop it. She is currently embarking on research relating to the development of PCK among educators involved in informal science learning.

Euripides Hatzikraniotis is Assistant Professor in the Department of Physics, Aristotle University of Thessaloniki, Greece. He obtained his physics degree and Ph.D. from the University of Thessaloniki. His research interests include the design and study of ICT-based environments for improving physics teaching and learning at different levels.

Avi Hofstein served for many years as head of the Department of Science Teaching and head of the Chemistry Group in this Department at the Weizmann Institute of Science in Israel. His scientific activities have focused on all aspects of the curricular process in the context of chemistry education programmes as well as in the programme 'Science for All'. His work has included curriculum development, implementation, professional development of both regular teachers and lead teachers and research on various aspects related to teaching and learning science (primarily chemistry). In recent years, he has been involved in several EU projects on technology education, focusing on continuous professional development of science teachers.

Philip Johnson taught chemistry for 13 years in non-selective secondary schools in England before joining Durham University School of Education, England, in 1992. He retired from the post of Senior Lecturer in Science Education in 2011. He began research into the development of students' understanding in chemistry whilst teaching in schools and continues to do so. For his Ph.D., he conducted a 3-year longitudinal study investigating the development of students' concept of a substance. His work is published in international science education research journals.

Loretta L. Jones is Emeritus Professor of Chemistry at the University of Northern Colorado, USA. She has a Ph.D. in physical chemistry and a DA in chemical education (University of Illinois at Chicago, 1979). In 2001 she chaired the Gordon Research

Conference on Visualisation in Science and Education. In 2006 she chaired the American Chemical Society Chemical Education Division. She is a Fellow of the American Association for the Advancement of Science and the co-author of chemistry textbooks and multimedia courseware. Her research focuses on helping students understand chemistry through visualisation.

Ajda Kahveci is Associate Professor of Chemistry Education at the Faculty of Education, Çanakkale Onsekiz Mart University, Turkey. She earned her Ph.D. in Science Education at Florida State University in 2005 analysing a programme in terms of its impact in encouraging undergraduate women to pursue science, mathematics and engineering majors. Her research interests include gender equity in science education, chemistry teacher education, inquiry-based chemistry education and chemistry misconceptions. She published her work in leading science education journals. More recently, she has served as external evaluator of proposals on inquiry-based science education methods submitted to the European Commission 7th Framework Programme.

George Kalkanis is a Professor of Physics Education and Information Technologies, Director of the Science, Technology and Environment Laboratory of the Department of Primary Education of the University of Athens and Invited Lecturer at the Physics Department. He worked for his Ph.D. thesis at Harvard-Purdue-Wisconsin experiment working for proton decay detection. His research interests include implementation of the educational model of microcosmos for the explanation of macroscopic phenomena as well as applications of digital technologies in education. He has published numerous books and articles on particles research and science education.

Maria Kallery is Assistant Professor of Didactics of Physics at the Aristotle University of Thessaloniki, Greece. She holds a B.Sc. in physics, an M.Sc. in computation and a Ph.D. in Science Education. She has taught science courses in secondary education for many years. Her publications include articles in International and European science education journals and collective volumes and books for physics and astronomy for young children. Her research interests include development of teachers' content and pedagogical content knowledge in science, action research, modelling of didactical activities and development of teaching and learning sequences.

Faik Ö. Karataş is an Assistant Professor in Chemistry Education at Karadeniz Technical University, where he teaches chemistry, pedagogics and the nature of science at both the undergraduate and graduate levels. He also serves as a member of Faculty Council in the Fatih Faculty of Education. He received his Ph.D. at Purdue for work on K-12 and undergraduate students' views of the nature of engineering.

Mageswary Karpudewan is a Senior Lecturer in the School of Educational Studies at the Universiti Sains Malaysia. She obtained her Ph.D. from the Universiti Sains Malaysia in 2010. Her Ph.D. research focused on integrating green chemistry experiments as laboratory-based pedagogy into chemistry teaching methods course and, thereafter, establishing its effects on pre-service teachers' environmental values, pro-environmental attitude, behaviour and achievement. The outcome of the integration has been published in numerous journals. Currently, she researches the possibility of integrating green chemistry experiments into secondary school chemistry curriculum.

Vangelis Koutalis is a Ph.D. candidate in the Department of Chemistry at the University of Ioannina. He has been an Allington Fellow at the Chemical Heritage Foundation (Philadelphia, USA) and visiting researcher in the Department of History and Philosophy of Science at Cambridge University, conducting research on the relationship between chemical experimentation and philosophical conceptualisations. He is also external research associate in the National Hellenic Research Foundation.

Joseph Krajcik serves as Director of the Institute for Collaborative Research in Education, Assessment and Teaching Environments for Science, Technology, Engineering and Mathematics (CREATE for STEM) at the Michigan State University. CREATE is a joint effort between the College of Education and the College of Natural Science to improve the teaching and learning of science and mathematics K-16. Throughout his career, he has focused on improving the teaching and learning of science by designing, developing, implementing and testing innovative learning environments that match what is known about student learning. He has authored and co-authored curriculum materials, books, software and over 100 journal manuscripts. He currently serves as co-editor of the Journal of Research in Science Teaching.

Rachel Mamlok-Naaman is a senior staff scientist and coordinator of the Chemistry Group at the Department of Science Teaching at the Weizmann Institute of Science in Israel. In addition, she is head of the National Centre for Chemistry Teachers at the Weizmann Institute of Science. She is engaged in development, implementation and evaluation of new curricular materials and research on students' perceptions of chemistry concepts. Her publications are in the areas of scientific and technological literacy, teachers' professional development, cognitive aspects of students' learning, assessment and curriculum development. In the last 3 years, she has been involved in three educational projects on the science education framework of the European Union.

Marijn R. Meijer carried out his Ph.D. studies on macro-micro thinking using structure-property relations at the Freudenthal Institute for Science and Mathematics Education at Utrecht University, the Netherlands. He took an M.Sc. in chemical engineering science and a postgraduate certificate in Education in Chemistry and the Science of Public Understanding at the University of Twente. He taught both school subjects for more than 10 years in secondary (high) school. He participated in several innovative projects related to recent developments in the chemistry and science curricula in the Netherlands. He recently became Director of the Dutch Chemistry Communication Center (C3).

Joi Merritt is a postdoctoral researcher in the Department of Teacher Education at Michigan State University, East Lansing in the United States of America. She obtained her Ph.D. in educational studies (science education) and B.S. in chemical engineering from the University of Michigan, Ann Arbor. Her research interests include developing genetics and chemistry curriculum materials and assessments to investigate K-12 student learning over time and examining teacher practice in relationship to student performance.

Tami Levy Nahum was a Senior Intern in the Department of Science Teaching, at the Weizmann Institute of Science in Israel, and is now a coordinator of the junior high school science team at the Branco Weiss Institute. Her research interests include inquiry-based laboratories, students' misconceptions and pseudo-conceptions, alternative assessment methodologies, teaching and learning chemical bonding and students' evaluative thinking capabilities in the Israeli multicultural context. She has been involved in the development of a new chemistry curriculum and in scores of professional development courses for junior high school and high school science teachers.

Canan Nakiboğlu is a full Professor of Chemistry Education in the Department of Secondary Science and Mathematics Education, in the Necatibey Education Faculty at Balikesir University. She obtained her B.S. in chemistry/physics education and M.Sc. and Ph.D. in inorganic chemistry. Her main research interests are learners' ideas, misconceptions and conceptual understandings; learners' cognitive structures; problem solving; teaching and learning in chemistry concepts; chemistry teacher education; teaching and learning through the chemistry laboratory; and V-diagrams.

Eng-Tek Ong is Associate Professor of Science Education in the Faculty of Education and Human Development at the Sultan Idris Education University, Malaysia. He obtained his Ph.D. from the University of Cambridge in 2005, investigating the character of smart science teaching in Malaysian schools and, thereafter, establishing its effects on students' attitudes, process skills and achievement. He has published numerous articles, reporting on the effective practice of science education. Currently, he and his co-researchers are developing and validating a science process skills inventory for primary school students.

George Papageorgiou is a Professor of Chemistry Education in the Division of Science and Mathematics, Department of Primary Education, Democritus University of Thrace, Greece. He obtained his B.Sc. (1984) and Ph.D. (1988) in chemistry from the Aristotle University of Thessaloniki, and he worked at the postdoctoral level at the School of Education, University of Durham, UK (2001). He has published numerous articles in chemistry, a significant number of which focus on students' and primary teachers' ideas, understanding and explanations of both physical and chemical phenomena.

Eleni Petridou is a science teacher in secondary education in Greece. She has a physics degree from the Aristotle University of Thessaloniki, Greece, and M.Sc. and Ph.D. from the Department of Primary Education of the same university. Her research interests include the use of models in science education and ICT-based environments for improving teaching.

Albert Pilot studied chemistry at Utrecht University in the Netherlands, with a major in analytical chemistry and a minor in educational research. His Ph.D. study

(1980, University of Twente) was on learning problem solving in science. In 1996 he was appointed as full Professor of Curriculum Development in the IVLOS Institute of Education, Utrecht University, and in 1998 as Professor of chemistry education in the Freudenthal Institute for Science and Mathematics Education of that university. His research in chemistry education is concentrated in the field of curriculum development, context-based education and professional development of teachers.

Dimitris Psillos is Professor of Didactics of Science and Educational Technology at the Department of Elementary Education, Aristotle University of Thessaloniki, Greece. He received a physics degree from the University of Thessaloniki and Ph.D. in science education from Exeter University, UK. He has taught undergraduate and postgraduate courses in didactics of science, educational technology and general physics. He has served as president of ESERA and has published books and papers in national and international journals. His research interests include modelling of students' and teachers' ideas and reasoning in science, models and modelling by students and teachers, developing and evaluating research-based innovative teaching-learning sequences and the development and study of ICT-based virtual laboratories for improving physics teaching at different levels. Currently he is responsible for the in-service education of science teachers section in a nationwide long-term project for training in service of primary and secondary teachers in the use of ICT.

Hannah Sevian is an Associate Professor in the Chemistry Department at the University of Massachusetts Boston. She earned a Ph.D. in 1992 in physical chemistry, did postdoctoral research in theoretical polymer chemistry and experimental materials science and taught chemistry at an urban public bilingual (Spanish) high school. Since 2001, she has taught undergraduate and graduate chemistry and education courses and worked closely with Boston Public Schools. Her current research focuses include a chemical design learning progression, cognitive processes in problem solving in chemistry and electrical engineering, effects of greener laboratory learning experiences on chemistry students' science identity development and K-12 science education policy in the implementation of science standards.

Constantine D. Skordoulis is Professor of Physics and Epistemology and Director of the Science Education Laboratory at the Department of Primary Education, University of Athens, Greece. He has studied Physics at the University of Kent at Canterbury, UK, and has worked as a visiting scholar at the Universities of Oxford (UK), Jena (Germany) and Groningen (the Netherlands). He is the Secretary of the Interdivisional Teaching Commission of the International Union of History and Philosophy of Science and also a corresponding member of the International Academy of History of Science (Paris).

Marilyne Stains is an Assistant Professor in the Chemistry Department at the University of Nebraska-Lincoln. She earned her Ph.D. in 2007 investigating the strategies that undergraduate (freshman to senior level) and graduate chemistry students engage in when solving classification tasks involving microscopic (i.e. drawings of molecules) and symbolic (i.e. H_2O) representations of chemical entities (i.e. chemical substances, chemical reactions). Her current research is focused on characterising (1) the extent to which chemical education research has impacted instructional practices at the postsecondary level and (2) the development of scientific knowledge during informal learning experiences.

Keith S. Taber trained as a teacher of chemistry and physics after completing a chemistry degree. Whilst teaching in schools and a further education college, he completed an M.Sc. in science education by research, and a doctorate, through part-time study. Shortly after joining the Faculty of Education at Cambridge, he was seconded for a year to be the Royal Society of Chemistry's Teacher Fellow. He is currently Reader in Science Education at Cambridge and chair of the Science, Technology and Mathematics academic group in the Faculty of Education. He is the editor of the journal Chemistry Education Research and Practice.

Vicente Talanquer is Professor in the Department of Chemistry and Biochemistry at the University of Arizona. He received his Ph.D. in chemistry from the National University of Mexico. His research seeks to understand how students' ideas and reasoning strategies evolve with training in a discipline. He has published numerous research articles in English and Spanish, and he is the author of ten science and chemistry textbooks for the elementary and middle school levels.

David F. Treagust is John Curtin Distinguished Professor at Curtin University in Perth, Western Australia, where he teaches courses in campus-based and international programmes related to teaching and learning science. He taught secondary science for 10 years in schools in England and in Australia prior to working in universities in the USA and Australia. His research interests are related to understanding students' ideas about science concepts and how these ideas contribute to conceptual change and can be used to enhance the design of curricula and teachers' classroom practice. David was President of the National Association for Research in Science Teaching (NARST) (USA) (1999–2001), is currently Managing Director of the Australasian Science Education Research Association and was the 2011 recipient of the American Chemical Society's Award for Achievement in Research for the Teaching and Learning of Chemistry.

Georgios Tsaparlis is Professor of Science Education at the University of Ioannina, Greece. He holds a chemistry degree (University of Athens), an M.Sc. and a Ph.D. in theoretical/quantum chemistry (University of East Anglia). He has taught and teaches physical chemistry (including quantum chemistry) and science/chemistry education courses. He has published extensively in science education, his research focus being on structural concepts, problem solving, teaching and learning methodology, teaching and learning physical chemistry and chemistry curricula. He was founder and editor (2000–2011) of *Chemistry Education Research and Practice* (CERP).

Suat Ünal is an Associate Professor and head of the Division of Chemistry Education at Karadeniz Technical University, where he teaches chemistry and pedagogics at both the graduate and undergraduate levels. He has a wide range of research interests including the determination of students' misconceptions, design and implementation of instructional materials to remediate students' misconceptions and enable conceptual change.

Marianne Wiser is Associate Professor and chair of the Psychology Department at Clark University in Worcester, MA, USA. She has a degree in physics and engineering (University of Liege) and a Ph.D. in cognitive and brain science (MIT). Her present work includes developing learning progressions for matter (preK-6) and for energy (3–5) and early elementary oral language curricula. She focuses on conceptual development and the interactions between concepts and language. She is a consultant on various projects related to the New Generation Science Standards and developing curricula and assessments based on learning progressions.

Ahmad Nurulazam Md Zain is Professor in the School of Educational Studies and also an Associate Research Fellow at the National Higher Education Research Institute, Universiti Sains Malaysia. His research areas include science education, higher education and computer education. He has directed and been involved in research projects funded by the World Bank, Danish Cooperation for Environment and Development, Malaysian Electricity Supply Industry Trust Account, Ministry of Education, Ministry of Higher Education and Ministry of Youth and Sports of Malaysia.

Introduction: Concepts of Matter – Complex to Teach and Difficult to Learn

Georgios Tsaparlis and Hannah Sevian

All things are made of atoms—little particles
that move around in perpetual motion,
attracting each other when they are a little distance apart,
but repelling upon being squeezed into one another.
In that one sentence ...
there is an enormous amount of information about the world.

Richard Feynman
(Feynman 1995, p. 4)

The *particle nature of matter* (PNM) is extremely important to the *disciplines of science*. It is central also to school science curricula worldwide, serving *as building block* for learning within a discipline (see chapter "Learning Progression Developed to Support Students in Building a Particle Model of Matter" by Merritt and Krajcik, this volume). It is a *threshold concept* providing a *portal* to an understanding of other fundamental topics (Meyer and Land 2006 – see also chapter "What Do We Know About Students' Beliefs? Changes in Students' Conceptions of the Particulate Nature of Matter from Pre-instruction to College" by Karataş et al., this volume). Last but not least, it has been identified as a *core idea* of the science content standards, with great emphasis placed in teaching certain of its aspects in Grades 8 through 12 (*National Science Education Standards*/National Research Council [NRC] 1996).

Before we proceed, it is essential that we distinguish between the terms *particulate* and *structural* concepts of matter. For Karataş et al. (chapter "What Do

G. Tsaparlis (✉)
Department of Chemistry, University of Ioannina, 451 10 Ioannina, Greece
e-mail: gtseper@cc.uoi.gr

H. Sevian
Department of Chemistry, University of Massachusetts, Morrissey Blvd 100,
02125 Boston, MA, USA
e-mail: Hannah.Sevian@umb.edu

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_1,

We Know About Students' Beliefs? Changes in Students' Conceptions of the Particulate Nature of Matter from Pre-instruction to College", this volume), PNM is used to describe phenomena ranging in size from individual atoms up to the nanoscale, in other words, objects between about 0.1 and 100 nm. Atoms or molecules constitute the so-called submicro-level, with a scale between 0.1 and 1 nm. *Subatomic particles* (electrons, neutrons, and protons) are also part of the submicro-world, while objects of materials >1 μm are described as *macroscopic*. Between the macro- and the submicro-scales lie the so-called meso-structures, for which other terms such as "microstructures" and "nanostructures" (the latter refer to the nanometer (10^{-9} m) scale) are also used (see chapter "Macro–Micro Thinking with Structure–Property Relations: Integrating 'Meso-levels' in Secondary Education" by Meijer et al., this volume). Most authors, however, maintain the term "particulate" to refer to particles such as atoms and molecules that are assumed "structureless." "*Structure*" can be defined as the spatial distribution of the components in a system (see chapter "Macro–Micro Thinking with Structure–Property Relations: Integrating 'Meso-levels' in Secondary Education" by Meijer et al., this volume); in particular, as the distribution of the electrons in an atom (electron configuration) or the arrangement and bonding of the atoms in molecule. Therefore, the term "structural concepts" is used to describe "*atomic*" and "*molecular structure*."

de Vos and Verdonk (1996, p. 659) considered the following to be correct scientific ideas about the PNM (see chapter "Understanding of Basic Particle Nature of Matter Concepts by Secondary School Students Following an Intervention Programme" by Treagust et al., this volume):

1. All matter consists of very small invisible entities called *particles*.
2. *Motion* is a permanent feature of all particles. There is a direct relation between the *temperature* of an amount of matter and the *average kinetic energy of the particles*.
3. In a gas, the empty space between particles is much larger than that occupied by the particles themselves. Particles of a gas in an enclosed space are randomly distributed.
4. There is *mutual attraction* between any two particles, but its magnitude decreases rapidly with distance. In a gas, the attraction is negligible, except at high pressure and low temperature.
5. In liquids and solids, the particles are much closer together and subject to *mutual attraction*. In solids, the particles may be arranged in regular patterns (*crystals*), with each particle being able only to vibrate around a fixed position. In liquids, the particles are irregularly arranged and move from place to place within a fixed volume.

The contribution of studies on the particulate and structural concepts to the development of the physical sciences is without doubt the cornerstone of modern science. Not only have these studies resulted in practical applications, they also have satisfied the innate philosophical disposition of human nature. It is therefore no surprise to find that particulate and structural models and concepts have been of keen interest to science teachers and constitute an integral piece of the backbone of modern science curricula even at the primary school level. Hence, the study of atomic and molecular structure – from the elementary models to the old quantum theory and later quantum mechanical concepts – is considered a sine qua non in science.

Science education research focuses on understanding and improving science learning by studying variables relating to the *content of science* or to "what the teacher or student does in a learning environment" (Herron and Nurrenburn 1999). It involves "a complex interplay between the more global perspective of the social sciences (i.e., the *process of learning*) and the analytical perspective of the physical sciences (i.e., the *content*)." These two perspectives are not independent of each other: knowledge of the *content* is a *necessary* but *not sufficient condition* for teaching science; it is knowledge of the *process of learning* and *the learner* that provides the *sufficient condition*.

Numerous and extensive studies in science education, conducted at various educational levels since the 1970s to evaluate the efficacy of instructional programs to assess students' understandings of PNM, have revealed poor understanding and great conceptual difficulties among students (Harrison and Treagust 2002). Various researchers (e.g., Abraham et al. 1994; Brook et al. 1984; Haidar and Abraham 1991; Lee et al. 1993; Novick and Nussbaum 1981) have investigated students' *alternative conceptions*. An international seminar was dedicated to the relation of macroscopic phenomena to (sub)microscopic particles (Lijnse et al. 1990). Ben-Zvi et al. (1990) confirmed that the root of many difficulties held by beginning students are due to the deficient understanding of the atomic model and how it is used to explain phenomenology and the laws of chemistry. Meheut and Chomat (1990) attempted to teach 13–14-year-old children how to build up a particulate model of matter by working out a sequence of experimental facts, starting from properties of gases (compression, diffusion), then moving on to solids, leaving the liquids last. On the other hand, Millar (1990) placed the emphasis on employing everyday contexts, using, for example, a piece of cloth (which is made of fabrics, made of threads, made of fibers) to move from the macro- to the submicro-level. The use of a textile thread (the "structural unit" of a piece of cloth) as well as of a brick (the "structural unit" of a house's wall) as analogues of the structural unit of matter has also been used by Tsaparlis (1989). Millar suggested that it might be wise to start with solids and postpone consideration of gases until later: many children need time and experience to appreciate that gases are really matter.

Finally, in a collective volume, Nussbaum (1998), after critically reviewing the various relevant propositions from the 1990 international seminar, coupled the *history-and-philosophy-of-science* approach with the *constructivist teaching* of models and theories on PNM. Vacuum physics is, according to Nussbaum, the right starting point for corpuscular physics. Only the existence of *vacuum* can justify *incontinuity of matter*, hence its *corpuscular/particulate nature*. In addition, *vacuum* allows for *motion of the particles*. Nussbaum based his introduction of the PNM on the study of air and other gases and maintained that the study of the PNM is a long process of *conceptual change*, in which students' wrong ideas can play a positive role.

The following are considered as major *impediments* to understanding particle concepts (see chapter "Understanding of Basic Particle Nature of Matter Concepts by Secondary School Students Following an Intervention Programme" by Treagust et al., this volume): (a) students' intuitive belief that matter is continuous in nature rather than particulate (Nakhleh 1992), (b) the belief that the particles in matter are in contact with each other with no empty spaces between the particles (Griffiths and Preston 1992; Lee et al. 1993; Nakhleh 1992), (c) the belief that matter in a substance is continuous and yet consists of particles (Johnson 1998; Krnel et al. 1998) – see also chapter "How Students' Understanding of Particle Theory Develops: A Learning Progression" by Johnson, this volume), and (d) the belief that the particles in a substance possess the macroscopic properties that are displayed by the substance (Andersson 1986; Ben-Zvi et al. 1986; Johnson 1998; Taber 1996; Tsaparlis 1989). Lee et al. (1993) found the strongly held notion among students that particles are in substances as opposed to the fact that substances are composed of particles, together with the belief of the presence of some kind of "stuff" or air between the particles. Students have acquired their intuitive ideas about the PNM during the early years of schooling and appear to change to scientifically acceptable understandings only to a limited extent after instruction (Stavy 1988).

An explanation of the difficulties occurs if one examines the relevant concepts from different perspectives of science education, some of which are seen as conflicting theories by many researchers. Tsaparlis (1997) has employed the following perspectives and arrived at the same conclusion about students' conceptual difficulties: (i) the Piagetian *developmental* perspective, (ii) the Ausubelian theory of *meaningful learning*, (iii) the *information-processing theory*, and (iv) the *alternative conceptions* movement. Herron (1978) maintained that concepts such as *atom* and *molecule* which have imperceptible examples *and* imperceptible attributes should be considered *formal* in the Piagetian sense; hence, it is quite likely that they cannot be totally understood without some formal reasoning. From the Ausubelian meaningful learning, as well as from the information-processing perspective, Johnstone (Johnstone 1991, 2000, 2007; Johnstone and Wham 1982) has used his well-known three-component triangle[1] to support that it is a mistake to imagine that all, or many, of our students can follow us up the middle of the triangle. In trying to sell the concepts of *element* and *compound*, we are simultaneously having to sell the submicro-concepts of *atom* and *molecule* and representing all this by *symbols*, *formulas*, and *equations*. We are in the middle of the triangle. This new kind of concept takes a long time to grow, but once we have embedded it in long-term memory, we can use it as a powerful way of looking at the world (Johnstone 1991). "The theoretical world of molecules, ions and electrons is not directly available to learners, so alternative conceptions are unlikely to be formed either by *direct* abstraction for experience, or by acquiring

[1]The submicroscopic level is further distinguished into one studying the properties of isolated molecules (represented at the highest level by quantum chemistry) and one studying the statistical behavior of large assembles of molecules (studied by the methods of statistical thermodynamics) (Ben-Zvi et al. 1990).

folk-knowledge (as talk about molecular structure and the like is seldom part of everyday life-world discourse)" (see chapter "A Common Core to Chemical Conceptions: Learners' Conceptions of Chemical Stability, Change and Bonding" by Taber, this volume). Taber considers teaching models and approaches partially to blame for the existence of a very common alternative conceptual framework.

This Volume

This contributed volume resulted from an international science education symposium entitled "Particulate and Structural Concepts of Matter" that Georgios Tsaparlis and George Kalkanis organized in Athens, Greece, from November 5 to 8, 2010. Subsequently, the contributed volume was organized, and manuscripts were taken through the peer review process and edited by Georgios Tsaparlis and Hannah Sevian. The volume includes 21 chapters, plus this introductory and a concluding chapter. Not all symposium presenters contributed manuscripts. In addition, several additional chapters were solicited by the editors of the volume in order to create a more complete collection of chapters. The symposium was originally organized by themes: learning progressions, mental models, early learning about particulate nature of matter, context-based teaching and learning, educational technology, chemical bonding, chemical reactions and phenomena, quantum mechanics and quantum chemistry, and history and philosophy of science. This contributed volume maintains these themes, but we have collapsed them into a smaller set.

The book is divided into six parts. In Part I, four chapters take a learning progressions approach to studying how students develop understanding of the particulate nature of matter. Learning progressions are empirically validated descriptions of pathways taken by students, over extended periods of time, toward achieving an *upper anchor* of scientific knowledge and/or practice. Recently, Duschl et al. (2011) contributed a comprehensive analytical review of learning progressions in science (see chapter "Implicit Assumptions and Progress Variables in a Learning Progression About Structure and Motion of Matter" by Sevian and Stains, this volume, for a summary of some of the findings). The four chapters in this volume illustrate some of the variations identified by Duschl et al. in their analysis, including how the boundaries of the learning progression are defined, how intermediate levels are studied, and the explicit or implicit model of conceptual change associated with the learning progression.

In Part II, seven chapters illuminate mental models held by preservice teachers, practicing teachers, and many educational levels of students, about various aspects related to the particulate nature of matter or phenomena requiring an understanding of matter's particulate nature. The approaches employed in the research studies reported include both intervention research and descriptive research (see chapter "Diagnostic Assessment of Student Understanding of the Particulate Nature of Matter: Decades of Research" by Kahveci, this volume, for definitions of these terms). The second-to-last chapter in Part II provides a review of studies at many different educational levels about how students' beliefs about the PNM change. The last chapter in Part II provides a review of diagnostic assessments to study student understanding of the particulate nature of matter and is organized according to these two classes of approach. These two chapters offer the reader an excellent overview of many recent and relevant studies of student understanding of the PNM and may be an excellent starting point for readers of this volume.

Part III of the book includes two chapters focusing on the production and use of educational technology tools for aiding students in understanding the particulate nature of matter. The first of these chapters provides an extensive review of the impacts of dynamic computer visualizations and summarizes implications for educators. The second of the two chapters offers a compelling example of how theoretical models used by practicing chemists can translate directly to improvements in teacher and student understanding of fundamental ideas related to the PNM.

In Parts IV and V, three and four chapters, respectively, treat two fundamental ideas of chemistry that build on understanding of the PNM: chemical reactions and chemical phenomena and chemical structure and bonding. The chapters include both intervention research and descriptive research, using a wide range of approaches and theoretical commitments.

Finally, Part VI includes two chapters. The first is an historical development of the concept of matter, from early roots in atomism in Greek philosophy and across controversies introduced through centuries of philosophical thought. The last chapter in the book, by the editors of the volume, attempts to synthesize the ideas that have been presented, and the problems that have been raised, in hopes of pointing toward new knowledge by the synergy that can result from realizing coherence and dissonance across a related set of research studies and reviews.

References

Abraham, M., Williamson, V., & Westbrook, S. (1994). A cross-age study of the understanding of five chemistry concepts. *Journal of Research in Science Teaching, 31*, 147–165.

Andersson, B. (1986). Pupils' explanations of some aspects of chemical reactions. *Science Education, 70*, 549–563.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education, 63*, 64–66.

Ben-Zvi, R., Silberstein, J., & Mamlok, R. (1990). Macro–micro relationships: A key to the world of chemistry. In P. L. Lijnse, P. Licht, W. De Vos, & A. J. Waarlo (Eds.), *Relating macroscopic phenomena to microscopic particles* (pp. 183–197). Utrecht: University of Utrecht, Centre for Science and Mathematics Education.

Brook, A., Briggs, H., & Driver, R. (1984). *Aspects of secondary students' understanding of the particulate nature of matter*. Leeds: University of Leeds, Centre for Studies in Science and Mathematics Education.

de Vos, W., & Verdonk, A. H. (1996). The particulate nature of matter in science education and in science. *Journal of Research in Science Teaching, 33*, 557–664.

Duschl, R., Maeng, S., & Sezen, A. (2011). Learning progressions and teaching sequences: A review and analysis. *Studies in Science Education, 47*(2), 123–182.

Feynman, R. P. (1995). *Six easy pieces: Essentials of physics, explained by its most brilliant teacher*. Reading: Helix Books.
Griffiths, A. K., & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*, 611–628.
Haidar, A., & Abraham, M. (1991). A comparison of applied and theoretical knowledge of concepts based on the particulate nature of matter. *Journal of Research in Science Teaching, 28*, 919–938.
Harrison, A. G., & Treagust, D. F. (2002). The particulate nature of matter: Challenges in understanding the submicroscopic world. In J. K. Gilbert, O. De Jong, R. Justi, D. F. Treagust, & J. H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 189–212). Dordrecht: Kluwer.
Herron, J. D. (1978). Piaget in the classroom. *Journal of Chemical Education, 55*, 165–170.
Herron, J. D., & Nurrenburn, N. C. (1999). Chemical education research: Improving chemistry learning. *Journal of Chemical Education, 76*, 1354–1361.
Johnson, P. (1998). Progression in children's understanding of 'basic' particle theory: A longitudinal study. *International Journal of Science Education, 20*(4), 393–412.
Johnstone, A. H. (1991). Thinking about thinking. *International Newsletter on Chemical Education, 6*, 7–11.
Johnstone, A. H. (2000). Teaching of chemistry – Logical or psychological? *Chemistry Education Research and Practice, 1*, 9–15.
Johnstone, A. H. (2007). Science education: We know the answers, let's look at the problems. In *Proceedings of the 5th Greek conference "Science education and new technologies in education"* (Vol. 1, pp. 1–11). http://www.kodipheet.gr/fifth_conf/pdf_synedriou/teyxos_A/1_kentrikes_omilies/1_KO-4-Johnstone.pdf
Johnstone, A. H., & Wham, A. J. B. (1982). The demands of practical work. *Education in Chemistry, 19*(3), 71–73.
Krnel, D., Watson, R., & Glazar, S. A. (1998). Survey of research related to the development of the concept of 'matter'. *International Journal of Science Education, 20*, 257–389.
Lee, O., Eichinger, D. C., Anderson, C. W., Berkheimer, G. D., & Blakeslee, T. D. (1993). Changing middle school students' conceptions of matter and molecules. *Journal of Research in Science Teaching, 30*, 249–270.
Lijnse, P. L., Licht, P., DeVos, W., & Warlo, A. J. (Eds.). (1990). *Relating macroscopic phenomena to microscopic particles*. Utrecht: CD-β Press.
Meheut, M., & Chomat, A. (1990). The bounds of children's atomism; an attempt to make children build up a particulate model of matter. In P. L. Lijnse, P. Licht, W. De Vos, & A. J. Waarlo (Eds.), *Relating macroscopic phenomena to microscopic particles* (pp. 266–282). Utrecht: University of Utrecht, Centre for Science and Mathematics Education.
Meyer, J. H. F., & Land, R. (2006). *Overcoming barriers to student understanding: Threshold concepts and troublesome knowledge*. Oxon: Routledge.
Millar, R. (1990). Making sense: What use are particle ideas to children. In P. L. Lijnse, P. Licht, W. De Vos, & A. J. Waarlo (Eds.), *Relating macroscopic phenomena to microscopic particles* (pp. 283–293). Utrecht: University of Utrecht, Centre for Science and Mathematics Education.
Nakhleh, M. B. (1992). Why some students don't learn chemistry: Chemical misconceptions. *Journal of Chemical Education, 69*, 191–196.
National Research Council [NRC]. (1996). *National science education standards*. Washington, DC: National Academy Press.
Novick, S., & Nussbaum, J. (1981). Pupils' understanding of the particulate nature of matter: a cross-age study. *Science Education, 65*, 187–196.
Nussbaum, J. (1998). History and philosophy of science and the preparation for constructivist teaching: The case of particle theory. In J. J. Mintzes, J. H. Wandersee, & J. D. Novak (Eds.), *Teaching science for understanding – A human constructivist view*. London: Academic, (Chap. 2).
Stavy, R. (1988). Children's conception of gas. *International Journal of Science Education, 10*, 553–560.

Taber, K. S. (1996). Chlorine as an oxide, heat causes molecules to melt, and sodium reacts badly in chlorine: A survey of the background knowledge of one A-level chemistry class. *School Science Review, 78*(282), 39–48.
Tsaparlis, G. (1989). What a single molecule does not look like – Two analogies and their effect on learning. Abstracts of papers of the *American Chemical Society*, 198: 176-Ched.
Tsaparlis, G. (1997). Atomic and molecular structure in chemical education – A critical analysis from various perspectives of science education. *Journal of Chemical Education, 74*, 922–925.

Part I
Learning Progressions for Teaching a Particle Model of Matter

Learning Progression Developed to Support Students in Building a Particle Model of Matter

Joi Merritt and Joseph Krajcik

Introduction

The particle nature of matter is a core idea in science. Core ideas are central to the disciplines of science and serve as the building blocks for learning within a discipline (National Research Council [NRC] 2012; Stevens et al. 2009). For example, the particle model of matter serves as the basis for understanding states of matter, phase changes, and properties of substances. In addition to being a core idea of science, understanding particle theory requires students to also understand the scientific practice of modeling. Providing an opportunity for students to develop science content and scientific practices over time is the approach advocated by researchers for the development of common science standards (NRC 2012). Recently, science educators have started to explore learning progressions as a means for understanding how students develop knowledge of complex science content over time (Corcoran et al. 2009).

Learning progressions are depictions of students' increasingly sophisticated ideas about a specific knowledge domain over time (NRC 2007; Smith et al. 2006). Learning progressions are not developmentally inevitable (Stevens et al. 2010) nor are they tied to a particular curriculum but do depend on instruction. However, learning progressions can provide the opportunity to examine how students' ideas evolve over time. The development and application of progress variables is one method that has been suggested as a means for tracking students' knowledge (Wilson 2005, 2009). Progress variables depict students' increasingly sophisticated conceptions over time, regardless of whether it is a matter of weeks or years.

J. Merritt (✉)
Department of Teacher Education, Michigan State University, East Lansing, MI, USA
e-mail: jmerritt@msu.edu

J. Krajcik
CREATE for STEM Institute, College of Education and College of Natural Science, Michigan State University, East Lansing, MI, USA
e-mail: Krajcik@msu.edu

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_2,

In addition, progress variables mediate between core ideas and specific concepts and skills being learned and serve as a means for monitoring student understanding during instruction (Wilson 2005, 2009). Once developed, progress variables can be used to provide information to both teachers and students about student development during instruction (Kennedy et al. 2006; Wilson 2005, 2009). Thus, learning progressions and progress variables could be powerful tools for promoting students' understanding of subject matter.

In their review of research on students' understanding of the particle model, Harrison and Treagust (2002) found that traditional curriculum materials present the particle nature of matter as a topic, focusing on the history of the atom. At the middle school level (ages 11–14) in the United States, students are often taught through direct instruction the structure of the atom and that the different states of matter are related to the movement and arrangement of atoms (American Association for the Advancement of Science [AAAS] 1993). This direct instruction assumes that once presented with the particle model, students will accept it as the correct model. For example, at the high school level (ages 14–18), a textbook presents the history the atom beginning with the Greek philosophers and ending with the current quantum model of the atom (Davis et al. 2006).

Moreover, research shows that students find it difficult to learn the particle model using traditional curriculum materials because they present particle concepts to students without helping them to develop these concepts, to take into account their prior knowledge, or to use them as models for explaining phenomena (Harrison and Treagust 2002; Krajcik 1991; Nakhleh 1992; Stevens et al. 2010). Often, students do not develop appropriate ideas because they never apply and reapply these ideas to explain phenomena. In this chapter, we describe a progress variable for the particle model of matter, evidence for this progression, and the importance of building students' ideas over time through key instructional experiences.

Literature Review of Student Conceptions of the Particle Nature of Matter

The particle nature of matter is a fundamental concept for learning and understanding many physical and chemical processes. Novick and Nussbaum (1978) studied students' ideas about the particle nature of matter as it relates to gases and found that students did not (1) internalize ideas related to the vacuum concept (empty space) and (2) understand the intrinsic motion of particles or the interaction between particles during a chemical change. Other studies have shown that students assign macroscopic properties of substances to the atoms/molecules that compose the substance (Ben-Zvi et al. 1986; Lee et al. 1993; Nakhleh 1992). Moreover, learners and many adults hold nonnormative science ideas regarding the structure of matter and how to explain phenomena. Our position is that student's prior knowledge of matter needs to be used as a resource to build understanding.

The nonnormative science ideas that students possess have been documented (Driver et al. 1985, 1994). For example, students misconstrue mass and size of an

Table 1 Students' nonnormative conceptions of particle theory

Attributing properties of substance to its atoms	Ben-Zvi et al. (1986)
Mismatch between the language students use for describing phenomena/matter and students' views of matter	Ben-Zvi et al. (1986), deVos and Verdonk (1996), Driver et al. (1994), Johnson (1998), Lee et al. (1993), Renstrom et al. (1990), and Taber (2003)
Language used in discussing the particle model	Ben-Zvi et al. (1986), deVos and Verdonk (1996), Driver et al. (1994), Johnson (1998), Lee et al. (1993), Renstrom et al. (1990), and Taber (2003)
Hybrid models	Johnson & Papageorgiou, 2010, Justi and Gilbert (2002), Liu and Lesniak (2006), Renstrom et al. (1990), and Taber (2003)

object. In other words, students hold the idea that a balled up piece of aluminum has more mass than if that same piece of aluminum foil was flat. In addition, it has been found that students have nonnormative ideas related to the particle nature of matter despite instructional strategies (Driver et al. 1994). Often they hold on to these ideas because they never see how the normative ideas can help explain phenomena they experience in their lives.

Researchers have also suggested that nonnormative ideas related to particle theory are developed during instruction. In some instances, instruction can be enveloped in prior malformed conceptions or learned due to the student's method of learning. As Harrison and Treagust (2002) note, "this practice of providing token evidence and making the assumption that students will accept the new ideas as fact is not an uncommon phenomenon in teaching and learning chemistry" (p. 191). Table 1 shows examples of some studies that have found different nonnormative ideas that students develop.

Students will often attribute properties of a substance to the atoms or molecules of that substance (Ben-Zvi et al. 1986; Lee et al. 1993). Ben-Zvi et al. (1986) designed a comparison study aimed at investigating students' views of matter. They found that although classroom discussions involved the correct terminology (i.e., atoms, molecules), one-third of students still attributed properties of a substance to its atoms. For example, students would come to the conclusion that gold atoms are yellow in color because a gold brick is yellow in color.

Lee et al. (1993) completed a comparison study that also found students were applying observable properties to molecules. In addition, they found that students had no concept of empty space between molecules, viewed molecules as being the same size as tiny objects (i.e., dust, bacteria, cells) and did not think molecules are constantly moving. These studies, as well as others focused on students' understanding of the particle nature of matter, often mention the mismatch between the language that students use for describing phenomena/matter and students' views of matter (Ben-Zvi et al. 1986; deVos and Verdonk 1996; Driver et al. 1994; Johnson 1998; Lee et al. 1993; Renstrom et al. 1990; Taber 2003).

As aforementioned, it is often taken for granted that students will just take up the particle model during instruction. Most curricula in the United States make no mention of alternative models students may hold. The only mention of alternative ideas relates to the delineation of the history of the atom found in many traditional textbooks (Harrison and Treagust 2002). This is a very scientific view of how the particle model developed, focusing on the scientists and the experiments that led to the current quantum model of the atom.

Besides the lack of acknowledgment of alternative student conceptions, there are issues related to the language used in discussing the particle model (Ben-Zvi et al. 1986; deVos and Verdonk 1996; Driver et al. 1994; Johnson 1998; Lee et al. 1993; Renstrom et al. 1990; Taber 2003). The particle model is important for explaining macroscopic phenomena using submicroscopic terms. For example, water boiling is explained as the rapid movement of water molecules from the liquid phase to the gaseous phase. In addition, the terms atom and molecule are often used interchangeably to describe materials on a submicroscopic level, which is often confusing for students and sometimes teachers (Taber 2003). For example, students are taught that elements are made up of atoms. Oxygen is an element that is made up of oxygen atoms, but these atoms are always found as oxygen molecules (two oxygen atoms bonded together). This becomes confusing for many students because they conflate the definition of element with the term atom. As Harrison and Treagust (2002) note, the "…semantic differences between students' and teacher's meanings for commonly used terms in science are a source of alternative conceptions" (p. 525).

Textbooks can also introduce hybrid models, which hinder students developing an understanding of the particle model (Justi and Gilbert 2002; Taber 2003). These hybrid models mix macroscopic descriptions of phenomena with particle and molecular ideas. For instance, they will show a diagram of water illustrating water molecules within a drawing of liquid water. This can result in students thinking of substances being made up of molecules, but they cannot identify the molecules as the substance (Johnson and Papageorgiou 2010; Liu and Lesniak 2006; Renstrom et al. 1990).

Curricula can also introduce "teaching models" that do not contribute to student understanding (Justi and Gilbert 2002; Taber 2003). "Teaching models" often are not based on scientific evidence, nor are they used for explaining scientific phenomena. Frequently, they are analogies that teachers use in an attempt to help students understand scientific content. When teachers present students with teaching models, they focus on the content of the model, not the nature of models and modeling and/or without emphasizing the role of modeling in developing what is known about the chemical behavior of matter. For example, students are introduced to the arrangement of atoms/molecules in the different states by having students behave as the molecules in the different states. This often leads students to viewing the spacing of atoms/molecules in a liquid to be closer to that of gases instead of being close together, like solids. Few efforts have been made to improve teachers' pedagogical content knowledge in this area (Justi and Gilbert 2002). Thus, in order to help students understand the particle model, teachers need to be aware of the various paths students take to a particle model.

In the field of chemistry, more than one model or representation is used to explain or illustrate different aspects of the same concept/phenomena. For instance, different models or representations highlight different aspects of data we have regarding the structure of water. Depending on the context of instruction, a water molecule can be discussed using a ball-and-stick model, a space-filling model, structural formula, or line-angle drawing. Each of these different models and representations highlight different features of water important to explaining a concept or phenomena. For example, a space-filling model shows the space that molecules take up as well as the angles at which the atoms in the molecules bond, while structural formulas show the relationship between atoms and types of atoms in a molecule. Furthermore, understanding these different models/representations is important for understanding more complex concepts such as hydrogen bonding or molecular models used to explain potassium channels in cell biology. Moreover, students have difficulty understanding how to interconvert between ball-and-stick models, structural formulas, space-filling models, and line-angle drawings (Baker and Talley 1972; Ferguson and Bodner 2006; Kozma et al. 2000). These difficulties stem from students not understanding the importance of these different representations in explaining different chemical concepts and how they are used to explain phenomena. Thus, for students to understand the significance of these different models, they need the skills to understand these different representations and how phenomena inform the creation of these models.

Others have shown or promoted using, creating, and understanding the nature of models as a means to help students understand physical phenomena (Grosslight et al. 1991; Harrison and Treagust 1998; Hestenes 1992; Justi and Gilbert 2002; MacKinnon 2003; Mikelskis-Seifert and Leisner 2005; Saari and Viiri 2003; Schwarz and White 2005; Schwarz et al. 2009; Vosniadou 1994). Unfortunately, students are often introduced to abstract topics like particle theory through the use of multiple models without understanding the nature of models. Teachers introduce different models (i.e., physical models, simulations, and 2-D models) based on the model's ability to explain different aspects of the same phenomenon. The various models utilized to represent specific phenomena confuse many students. This is especially true for the teaching of abstract concepts in which analogies and models can be confused with reality. Moreover, teachers should help students to understand shared and unshared attributes of models as well as the limitations of different models (Harrison and Treagust 1996). Thus, students not only need help in understanding models used to explain particle theory, but they also need instruction that helps them to understand the limitations of these different models.

Several studies indicate that students' development of a particle model of matter takes different paths and that, as students' content knowledge grows, students' models can change – both toward a more complete particle model and back to their initial understanding (Johnson 1998; Margel et al. 2008; Nakhleh et al. 2005). Johnson (1998) found students' models correspond with their explanation of phenomena, such that a continuous model relates to macroscopic explanations of phenomena while a complete particle model relates to submicroscopic explanations of phenomena. Margel et al. (2008) found a similar pattern of students moving from a macroscopic to molecular model as well as macroscopic to molecular explanations within a 3-year curriculum in Israel. On the other hand, Nakhleh et al. (2005) found that students were able to give submicroscopic explanations for familiar substances, but their understanding was fragmented based on particular substance or phenomena.

In sum, students' understanding of matter originates both from everyday experiences and classroom instruction. As such, students' conceptions should not be looked upon as misconceptions but as resources for developing greater knowledge. In addition, student nonnormative ideas have provided insight into how student understanding of the particle model develops over time. This development perspective provides opportunity to (1) track student understanding during instruction, (2) determine students' prior knowledge, and (3) gain an understanding of how this knowledge changes through instructional interventions. Moreover, the ability to track student progress also serves as insight into how instruction impacts these changes. The development and application of progress variables is one method that has been suggested as a means for tracking student understanding (Wilson 2005, 2009).

The sixth grade chemistry unit described in this chapter takes the approach of focusing on students' models of matter and the application of that model to explain macroscopic phenomena (Ben-Zvi et al. 1986; Kozma et al. 2000; Justi and Gilbert 2002; Harrison and Treagust 2002; Snir et al. 2003). Specifically, the development of a particle view of matter is the basis for understanding properties, states of matter, and phase changes. In addition to the development of particle model, students develop an understanding of the practice of modeling. Moreover, we conducted research to examine how students' understanding of the particle nature of matter changed as they participated in this contextualized and model-based chemistry unit. In this chapter, we examine how the curriculum supported students' development of a particle view of matter using an empirically validated particle model of matter progress variable.

Learning Progressions and Progress Variables

As mentioned earlier, learning progressions depict students' development of more sophisticated conceptions of a specific domain over time (NRC 2007; Smith et al. 2006). Learning progressions are not developmentally inevitable as student understanding depends on instructional activities (Stevens et al. 2010). In other words, the order in which ideas are presented and built upon during instruction is a factor in how learning progresses. However, it is possible to gather evidence to show how students develop when a learning progression is either tied to key instructional tasks or curriculum. Moreover, learning progressions provide an opportunity to examine students' increasingly sophisticated ideas over the long term.

Learning progressions are also a means for helping both students and teachers to track students' knowledge over time (NRC 2007; Smith et al. 2006). Moreover, learning progressions provide a means for thinking about how to present topics to students so that they build on each other through the years. Smith and colleagues (Smith et al. 2006) progression is based on prior research related to matter and particle theory and focuses on students gaining more sophisticated understanding of matter and its properties as well as applying microscopic explanations to macroscopic phenomena. In addition, this progression identifies which topics are introduced each year and how knowledge is built in relationship to what students have previously learned. Developing a means for tracking students' long-term progress for understanding the core ideas of science is important. We also need to track students' increasingly sophisticated understanding of concepts underlying these core ideas, especially within the time frame of classroom instruction.

Progress variables represent a range of student thinking about a particular knowledge domain or construct. In other words, progress variables describe the construct or core idea that we want to track. A construct "can be part of a theoretical model of a person's cognition…their understanding of a certain set of concepts" (Wilson 2005, p. 6) and is considered a latent trait that can be measured (Wilson 2005). Like learning progressions, constructs range from low to high knowledge of a domain, with increasing complexity occurring over time. Thus, progress variables can mediate between core ideas and specific concepts and skills being learned, taking into account what research has revealed about student learning in a particular domain. For instance, one or more progress variables could be used to track student understanding of a particular construct over various time frames as short as a curriculum unit to a learning progression that covers multiple years (Wilson 2009).

Therefore, progress variables allow one to focus on student growth of a construct over time (Wilson 2005, 2009). In addition, each unit of instruction contributes to students' progress, which necessitates that assessment aligns with one or more progress variables. Consequently, both what students are learning must be clearly defined and a theoretical framework for interpreting students' progress is necessary to establish the construct validity of an assessment system (Wilson 2009). Constructs are latent traits we cannot see, so we develop measures within the context of the classroom to serve to make students' thinking visible (NRC 2001). Thus, summative and embedded assessments must be aligned with the progress variable. Alignment of assessments with instruction "allows the creation of a calibrated scale to map the growth of students so teachers and researchers can track the progress of individual students as they undergo instruction" (Wilson 2005, p. 195). As a result, assessments must reflect the variety of instructional practices of the curriculum. Thus, the variables serve as a means for relating curriculum to standards as well as to assessment that are not related to the curriculum. Once developed, progress variables can be used to track student understanding of scientific content and practices, providing information to both teachers and students about student progress during instruction (Kennedy et al. 2006; Wilson 2005, 2009).

Progress variables are visualized through construct maps, which divide the complex levels of students' increasingly sophisticated understanding into distinguishable levels. Thus, a construct map specifies how a construct develops over time. In turn, a single construct map could be designed to represent a learning progression, or several related construct maps could be developed to track a single learning progression. When a construct map is developed in relationship to innovative curriculum, the construct map also represents the goals of teaching (Wilson 2009). The development of the construct map is also important because assessments for tracking students' understanding must align with construct map.

The particle model of matter (PMM) progress variable was developed in relationship to the Investigating and Questioning our World through Science and Technology (IQWST) (Krajcik et al. 2012) [discussed later] sixth grade chemistry unit (see Table 2). The PMM progress variable was developed to determine how student understanding of the particle nature of matter changes during instruction (Merritt 2010). The curriculum focuses on student development of a particle view of matter using models of matter that they construct. We developed this construct map by an iterative process of considering the logic of the discipline, what was known about how students' ideas regarding the particle model, and empirical work based on the curricular intervention.

This map illustrates how students' understanding of the particle model builds over time. The "particle model" construct map encompasses both the varying starting points students had before the curriculum began and their varying end points, with the least sophisticated understandings at the "descriptive model" level (bottom of table) to most sophisticated at the "complete particle model" level (top of table). This map reflects students' increasingly sophisticated understanding of the particle model as it relates to properties and phase change, starting from the "descriptive model." It also takes into account the instructional sequence in order to move students from one level to the next level. For example, the unit focuses on developing a particle model to understand structure of matter before applying the model to explain properties and then phase changes. The "example student response" column shows actual student responses, which demonstrate the types of understandings students exhibit at each level. The "progressing to next step" column illustrates examples of instructional strategies that could help students reach the next level (e.g., progress from a descriptive to a mixed model).

Students at the descriptive model level have a macroscopic view of matter that can explain phenomena using qualitative descriptions. Students describe ice as water in the solid state. Mixed model level students are beginning to develop a particle model but blend the particle model with the descriptive model. At this level, students view some substances on a macroscopic level and others as particles and do not identify particles as atoms or molecules. For example, they would describe water in the liquid state as being composed of particles within the liquid. Students at the basic level students use a particle model of matter to explain phenomena. At the basic level, the particle model can include atoms or molecules but have difficulty explaining the movement or arrangements of atoms/molecules in different states. However, students at this level can explain that different substances have different properties due to the arrangements of its atoms. Though the model is more scientifically accurate, students still hold incomplete understandings about the spacing between atoms/molecules in the different state. For example, students often think molecules of a liquid are more spaced apart than those in a solid. At the

Table 2 Particle model of matter construct map

Category	Description	Example student response	Progressing to next step
Complete particle model	Students use particles (molecules) to explain phenomena. There is empty space between the particles. The students are able to *distinguish spacing AND motion relevant to the particular state* they are in. Different substances have different properties because they are made of different atoms OR have different arrangements of same atoms	Water vapor, liquid water, and ice are all made up of water molecules. The molecules in water vapor are far apart and move around freely. In a liquid, they are closer together but move around each other. In a solid, they are close together and vibrate Sugar and water are not the same because they are made up of different molecules	
Basic particle model	Students use *particles* (may use atoms and/or molecules) to explain phenomena. There is an empty space between the particles. Students have difficulty in explaining the difference in spacing in different states and/or are unable to distinguish the difference in movement for all states. *Different substances have different properties because they are made of different atoms or have different arrangements of same atoms*	Water vapor is made up of water molecules that are spaced far apart and move freely everywhere. Liquid water is made up of water molecules that are moving but are closer together than in water vapor. In ice, the molecules are even closer together Sugar and water are not the same because they are made up of different molecules	Students need to understand the difference in movement of a substance in different phases. For example, a simulation of the same substance as a solid, a liquid, and a gas should include the same representation for water molecules but with different spacing and movement, including how movement changes as temperature changes

(continued)

Table 2 (continued)

Category	Description	Example student response	Progressing to next step
Mixed model	Students use both *particle* and *descriptive ideas* to explain and describe phenomena. Though they recognize that different substances have different properties, their explanation for why remains at a macro-level	Water is made up of water particles. The water particles exist within the liquid water. Thus, in between the particles is liquid water	The idea that water is made up of the same atoms/molecules no matter the state should help students to realize that a substance's atoms/molecules do not change. For example, a model of ice, water, and water vapor should include the same representation for water molecules but with different spacing and movement
Descriptive model	Students describe objects *exactly as they appear*. When an object is broken into smaller pieces, it always has the same properties	Water is a clear, colorless liquid. Ice is a "clear" solid. They have different structures and are described differently. Therefore, they are not the same substances	The ideas that objects are made up of parts could be a useful idea to help students realize that a piece of a substance that looks continuous can be broken down into smaller pieces. Student needs to realize that a substance is changeable (it can change phases) or, in other cases, may be broken into smaller pieces

Table 3 National standards (AAAS 1993; NRC 1996)

AAAS 4D/M1: All matter is made up of atoms, which are far too small to see directly through a microscope. The atoms of any element are alike but are different from atoms of other elements. Atoms may stick together in well-defined molecules or may be packed together in large arrays. Different arrangements of atoms into groups compose all substances
AAAS 4D/M3: Atoms and molecules are perpetually in motion. In solids, the atoms are closely locked in position and can only vibrate. In liquids, the atoms or molecules have higher energy, are more loosely connected, and can slide past one another; some molecules may get enough energy to escape into a gas. In gases, the atoms or molecules have still more energy and are free of one another except during occasional collisions. Increased temperature means greater average energy of motion, so most substances expand when heated
NRC B5-8: 1A: A substance has characteristic properties, such as density, a boiling point, and solubility, all of which are independent of the amount of the substance

complete level, students have a particle model that can explain states of matter, phase changes, and differences in properties of substances. Students at this level describe water as being composed of water molecules and can describe the arrangement and movement of molecules in the different phases.

The Curriculum

The Investigating and Questioning our World through Science and Technology (IQWST) curriculum (Krajcik et al. 2012) takes the approach of building a student's understanding of core ideas over time. In the sixth grade *How can I smell things from a distance?* unit (Merritt et al. 2012), students develop understanding of the particle nature of matter model by using and refining the model to explain phenomena, such as states of matter, phase changes, and properties. For example, the particle model can be used to explain a property like boiling point. The boiling point of a substance occurs at a fixed temperature and involves the rapid evaporation of anywhere in a bulk liquid. During heating, particles gain energy and move faster. At the boiling point, the energy of these molecules is enough to overcome the attractive forces of the other liquid molecules so that it goes from the liquid to the gas phase.

Identifying and Unpacking Standards

For the development of this unit, we identified three standards (see Table 3) from the Benchmarks for Scientific Literacy (AAAS 1993) and National Science Education Standards (NRC 1996). Although IQWST was developed prior to the National Research Council's New Framework for K-12 Science Education (NRC 2012), the ideas in this unit correspond to ideas that all learners should understand by the end of eighth grade in the Structure and Properties of Matter core idea (Physical Science 1.A). The identification of a small number of standards sets the IQWST curricula apart because of our focus on depth instead of breadth.

Once the standards were identified, we underwent a process of unpacking what it means to teach them. Unpacking, in this instance, means we carefully read through the standard to identify concepts within them which are important, what knowledge students may bring to these ideas, what prior knowledge is necessary and what misconceptions students have as well as to what depth these concepts should be explored, in this case, in sixth grade (Krajcik et al. 2008).

For example, the first standard (AAAS 4D/M1) begins with the idea: All matter is made up of atoms. We determined that this idea was composed of two concepts: (1) that matter is made up of particles and (2) that these particles are atoms. Then, we determined that students need to understand what matter is – anything that has mass and takes up space. From research and our experiences, we identified that students would have difficulty in differentiating weight and mass as well as difficulty in identifying air and other gases as matter (Driver et al. 1985, 1994). Additionally, we looked at what prior knowledge students should have of matter based on the preceding national standards. In some instances, as we unpacked the standards, we also identified what concepts students would not be expected to learn at this time. For example, students are not expected to understand that a single atom has the chemical properties of that element, but it takes several atoms to give the element its physical properties.

This process of clarifying and elaborating the standards helped to ascertain what it means to teach sixth grade students the particle nature of matter and how the particle model is used to describe states of matter, as well as explain phase changes and properties. Unpacking process also helped to identify what ideas needed further support for students (Krajcik et al. 2008). For instance, helping students understand that matter is anything that has mass and volume is a fundamental concept for helping students to understand both states of matter as well as developing a particle view of matter. Students often conflate the terms mass and volume. Therefore, the decision was made to include activities for students to measure mass and volume as well as to include discussions of matter and volume on both macroscopic and microscopic levels when discussing states of matter. In the United States, students often enter the sixth grade with underdeveloped ideas of these two important concepts. From this work, we were able to develop a unit that contains three learning sets and corresponding assessment items.

The unpacked standards were then used to construct learning performances that serve as the unit learning goals (Table 4). A learning performance results from combining the content standard with an inquiry standard. These learning performances clearly specify what students are expected to be able to do with the knowledge described in the benchmark. Moreover, they "serve as the learning goals that guide development of learning activities and assessments" (Krajcik et al. 2008, p. 7). Thus, in this unit students use the particle model of matter to explain phenomena related to states of matter, phase changes, and properties (see Appendix for a complete list of learning performances).

Table 4 Example of a learning performance

Content standard	Inquiry standard	Learning performance
AAAS 4D/M3: Atoms and molecules are perpetually in motion. In solids, the atoms are closely locked in position and can only vibrate. In liquids, the atoms or molecules have higher energy, are more loosely connected, and can slide past one another; some molecules may get enough energy to escape into a gas	Develop…models using evidence (NRC 1996, A: 1/4, 5–8) Models are often used to think about processes that happen… too quickly, or on too small a scale to observe directly… (AAAS 1993, 11B: 1, 6–8)	Using the particle model, students will explain phase change from a solid to a liquid

We use a driving question to contextualize students' learning of the particle model of matter. The driving question (Krajcik and Blumenfeld 2006) provides a real-life context to engage students in learning about scientific ideas to explain phenomena. The driving question for the unit is "How can I smell things from a distance?" Thus, the anchoring context of the unit has students smell different odor-producing objects and create models to explain how they smell the object from a distance. Throughout the unit, students engage in phenomena, creating models to explain to explain them and use the evidence they gather to help them answer the driving question. In other words, as students experience the unit, they create models to explain phenomena and revisit and refine their models based on what they have learned from these other experiences.

Second, the unit involves the creation of student artifacts, the models that students create. Students experience various phenomena throughout this 8-week unit to help them to gain knowledge and understanding of the different aspects of the particle nature of matter. Key phenomena were placed throughout the unit to help build student understanding and take it to the next level. Peer-to-peer and whole class discussions are utilized to help students discuss and critique their models and understand scientific concepts.

Our approach also provides students with opportunities for using multiple models when students are initially developing their modeling skills. In this case, the use of multiple models refers to students creating and discussing a variety of models of matter (including their peers' models). In addition, teachers lead discussions of student models to help students understand both the particle nature of matter and the purpose of creating models.

Our curriculum work builds from the foundational 1978 Novick and Nussbaum study. Novick and Nussbaum found that students least internalized aspects of the particle nature of matter that opposed their sensory perception of matter. The aspects relevant to our study are that matter exists as tiny particles, empty space (the vacuum concept), and intrinsic motion (particle kinetics). These aspects tend to lead students to forming a continuous-particle model. In particular, students cannot conceive of empty space in ordinary matter, including gases. In designing our unit, we also made use of innovative ideas from Joseph Nussbaum's development of curriculum materials in Israel on the particle nature of matter.

Based on the findings of the 1978 Novick and Nussbaum study, the first learning set of the unit focuses on the following:

- Bulk properties of gases that may make it difficult for students to accept the idea of empty space and various properties of gases (addition, subtraction, compression, and expansion of a gas; air has mass and volume).
- Relationship between heat and speed of motion to understand the intrinsic motion of particles.
- Exposure to more phenomena that are dissonant with their sensory perception of matter would lead to greater accommodation of the particle conception of matter.

The unit contains three learning sets (see Appendix for brief descriptions of the lessons in each learning set) and takes approximately 8–10 weeks to complete. The first learning set (Lessons 1–5) aims at helping students understand what matter is (anything that has mass and volume and exists in one of three states). Students investigate the melting and freezing of menthol to understand that substances can exist in more than one state as well as that they can undergo changes in state. Students also investigate the properties of air (expansion, compression, addition, and removal) to develop a particle model of matter. They realize that gas within a fixed volume can be compressed or expanded using a syringe. And that gas can be removed from a flask of a fixed volume. Students use these four properties to develop a particle model of matter that can account for these four phenomena. By the end of the first learning set, the class develops a consensus model of matter in which matter is composed of particles, there is empty space between particles, the particles are constantly moving, and that particles have mass and occupy space.

Learning Set 2 (Lessons 6–9) helps students to identify and explain properties of substances (elements and compounds), including that properties are a result of the arrangement of atoms in a substance. Students investigate the properties of elements to understand that different substances have different properties. They use their particle models to explain that these differences result from the elements being composed of different types of particles and these particles are atoms. Later, students smell different substances, for which they only see their chemical formulas. From this experience, students develop understanding that the different arrangements of atoms in a molecule (some substances have the same formula, but different odors) result in different properties.

Learning Set 3 (Lessons 10–15) involves students using their models of matter to explain phase changes. Students investigate the effect of heating and cooling on the ability for ammonia to change the color of indicator paper. Students use their particle models to explain this phenomenon, phase change – boiling, condensation, melting, and freezing as well as evaporation. By the end of the unit, students revisit and revise their consensus model based on what they have learned throughout the unit.

The anchoring activity of the unit has students create models (student models are defined as their drawing of gases at the molecular level plus explanation) to explain why they think they can smell an object from a distance. The modeling activity of Lesson 1 is not only a way for teachers to elucidate students' initial notions of the particle nature of matter but is also an activity that is repeated during and at the middle and end of the unit to assess and monitor students' progress.

The smell unit is also designed to be educative for teacher. Educative curriculum materials are designed to promote teacher learning (Davis and Krajcik 2005). As mentioned earlier, teachers need to understand the practice of modeling, the hybrid models of matter, and student misconceptions of matter. As such, the unit includes teacher boxes to help teachers in understanding models (and the particle model in particular), common student ideas (or misconceptions) and ways to help students with these ideas, and subject matter knowledge. In addition, descriptions of the types of discussions they should use to help students in understanding the scientific content, phenomena they are experiencing, and about the models the students are creating throughout the unit. For each discussion, the purpose for having the discussion, suggested questions, and a rational for why these questions help student understanding and what ideas the students should gain from the discussion are explicated.

Teachers' Role in Curriculum Development

Teachers played a vital role in the development of the unit. During the initial development phase of the unit, teachers helped to select the driving question and develop the learning goals of the unit. After a 2-h professional development session for three lessons, one teacher piloted these initial lessons of the unit to help us to determine whether having students create and critique their own models of matter would be an effective instructional strategy. These lessons were all videotaped, and the teacher provided us feedback on these initial lessons immediately following instruction.

The entire unit was piloted by teachers for 2 years prior to national field trials. The teachers received professional development prior to enactment. In the first year, one teacher piloted the unit. A researcher was in the classrooms almost daily, videotaping enactment and providing support when needed. In addition, the teacher contacted us via email with questions, comments, and/or feedback. The teacher filled out evaluation forms to provide feedback on the lessons. At the end of the enactment, we met with the teachers to go over their feedback. This feedback was one part of the information used to modify the unit.

This same process followed in the second pilot year, in which six teachers from across the United States participated in piloting the unit. Teachers received

3 days of face-to-face professional development and online support through a message board where they could post questions and discuss issues with each other as well as researchers. Researchers also videotaped three of the teachers' enactments. The other sites also received support from researchers through site visits. Teachers filled out surveys to provide feedback at the end of each learning set as well as at the completion of the entire sixth grade unit. The feedback was used to revise unit.

Our review of the literature informed us about students' conceptions of the particle nature of matter. This information was used both in the development of the curriculum as well as our construct map. The construct map that was developed both incorporates student conceptions of matter as well as reflects the goals of the curriculum. Next, we discuss how the construct map was used to track students' progress during instruction.

Supporting Student Development of a Particle Model of Matter

This study investigated how students' understanding changed as they engaged in a contextualized model-based chemistry unit aimed to help them to develop a particle model of matter. The overarching question guiding this study was: *How does middle school students' understanding of the particle nature of matter change during enactment of a model-based unit?* This study was a part of a larger study in which the PMM progress variable was validated. Six hundred and two students and their seven teachers were involved in the study (Merritt 2010). The larger study focused on students' gains in knowledge of particle theory from pretest to posttest. These identical pre-/posttest assessments were found to be valid and reliable measures of student performance (Cronbach α of 0.85 for the assessments). In this study, we investigated the use of the particle model of matter progress variable to track student learning during the curriculum. In addition, we examined how the instructional strategies of the curriculum supported student development of a particle view of matter.

This study involved three teachers from three different schools in three different cities and 122 students of varying proficiencies. Each teacher had taught the unit previously. We collected identical pre-/posttests and embedded assessments from three schools in the Midwest and Southwest United States. School 1 was located in a Midwest rural town of varying socioeconomic status. Forty-three students from school 1 participated. School 2 was located in a suburb of a large Midwest city and the teacher has taught the unit for 3 years. Fifty-eight students participated from school 2. School 3 and its 21 students are located in a midsize urban city in the Southwest. The students are not a representative sample of all students that participated in the study but are students who completed all three embedded assessments (AS1.1, AS5.2, and AS15.2) that were included in the study. Students' understanding of the particle model of matter was tracked using pretests, embedded assessments, and posttests.

Teachers' Professional Development

Teachers received two half-day professional development sessions for the chemistry unit in the summer. These sessions introduced teachers to the anchoring context of the unit and how creating and using models support students in developing a PMM. Prior to enactment of the chemistry unit, teachers also received 2 days of professional development. The professional development encompasses teachers experiencing the major investigations of the unit as well as creating models that help explain the phenomena that they observed. In addition, teachers were introduced to the scoring rubric that we use for assessing student work. Student work from previous pilots of the unit was used to help teachers evaluate students' knowledge as well as to help teachers in understanding how to facilitate discussions based on students' models of matter.

In addition, teachers received online support as members of an online support group by posting questions, discussing issues, and sharing ways to deal with issues that arose during enactment with each other and facilitators. Researchers made visits to a few schools, but not all schools had available local support.

Student Artifacts

Data collection included identical pre- and posttests composed of 11 multiple-choice items and three written response items. The multiple-choice items covered the key learning goals of the unit: particle nature of matter, matter, phase change, and properties. Two of the written response items required students to create models to explain phenomena, and the third item focused on students explaining how two substances could be differentiated from each other based on their properties. The results of the pretest served to provide insight into students' prior knowledge. The three embedded assessments from the sixth grade chemistry were used to track student progress in developing a particle model of matter. These similar embedded assessments occur during Lesson 1, Lesson 5, and Lesson 15. The embedded assessment for Lessons 5 and 15 are slightly different in that students are asked additional questions, for example, comparing their current models with their previous models and identifying why they made their changes based on what they had learned. For the purpose of this study, only the student models (Question 3), which encompass a key (Question 4), their drawing, and explanation (Question 5) in all three activities, were analyzed (AS1.1, AS5.2, and AS15.1; see Fig. 1).

Scoring

The pre-/posttest was scored using a scoring guide. Multiple-choice items were scored dichotomously; thus, correct responses received a "1" and incorrect responses received a "0." Scoring guides were developed for written response

Name ____________ Date ____________

Activity 1.1

Can you Smell What I Smell?

PURPOSE

In class, your teacher opened a jar that had an object in it. The object in the jar had an odor to it, and the odor moved across the room. In this activity, you will record your ideas about how an odor can go from an object to your nose.

DATA COLLECTION/OBSERVATION

1. Write the odor you smell

____

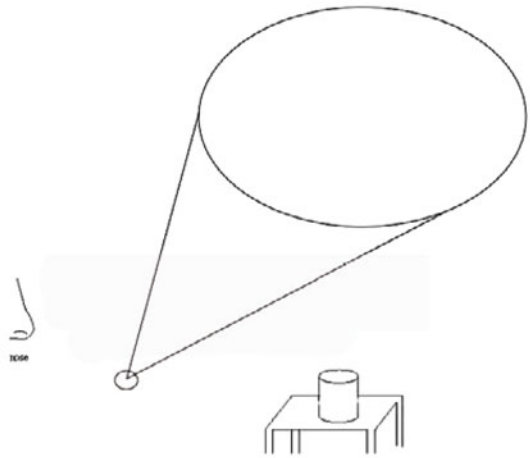
2. Describe what happens when your teacher opens the jar.

____

____

____

3. Imagine that you have a very powerful microscope that would allow you to see the odor up really, really close. What would you see? Create a drawing that shows how the odor got from the source to your nose. The large circle in the drawing below represents the magnified part of the air between the jar and your nose. In the circle, draw a picture of what you think the odor looks like between the jar and your nose.



4. Label what the parts in your drawing represent.

6th Grade Chemistry Activity 1.1 1

Fig. 1 Modeling embedded assessment for activity 1.1

Table 5 Scoring guide for explanation portion of smell model embedded assessment items

Code	Level description	Examples of actual student responses
	No response	
0	Descriptive – describes model OR describes what happened in class OR gives completely incorrect explanation OR uses prior experience to explain what is happening	It shows how odor [travel] through air. OR The lines where ammonia and little circles are air [particles] and arrows were movement
1	Mixed model Student tries to explain odors traveling from the source to the nose but uses the incorrect mechanism or focuses on a macrolevel	The air and scent go faster [with] more heat and slower [with] less heat. OR The fan blows air into the air blowing over the tuna smell picking up the smell traveling in a straight path to the nose. OR The odor molecules mix in the air and flow up the nose
2	Basic particle model Student is able to explain that odor molecules travel from the source to the nose. Student may explain how air helps in this process	The [odor] is in a gaseous state. The air and odor molecules spread around the room
3	Complete particle model Student is able to correctly explain on a submicroscopic level the movement: odor particles travel in air, random collisions of odor, and air molecules. Student may also describe sublimation/evaporation from the source on a submicrolevel	First, the ammonia particles gain enough energy to evaporate and turn to gaseous ammonia. Then it moves in a straight path [until] it runs into something. Eventually it travels to a nose

and embedded assessment items. These guides take into account actual student responses to the item as a means for mapping them to the different levels of the construct map. Table 5 is the scoring guide for the written response portion of the embedded assessment item in which students are explaining to a friend how an odor can travel from its source to their noses using their drawing (see Fig. 1). For example, the "basic particle model" level of the construct map indicates that students recognize that particles travel from the source to the nose, but unlike the "complete particle model" level, they cannot describe the random motion of the particles.

The written response items were scored with one other rater, obtaining inter-rater reliability of 94.4 %, which was determined by coding nine pre-/posttests, and then dividing the number of items coded identically by the number of items coded. The embedded assessments were also scored using the scoring guide. An inter-rater reliability of 89 % was obtained, which was determined by coding nine embedded assessments, then dividing the number of items coded identically by the number of items coded.

Data Analysis

We used a one-dimensional partial credit Rasch-based model with maximum-likelihood estimation (MLE) because the test includes multiple-choice items that cover a single level of the construct map as well as items that cover multiple levels of the construct map. By using this model, we were able to estimate student proficiency estimates and item difficulty on the same scale. This common scale allowed us to describe students' expected performance based on their estimated proficiency in comparison to estimated item difficulty. When a respondent's proficiency and the item difficulty are at the same location, there is a 50–50 chance of them getting the item correct. When the respondent's proficiency is above an item, they have a greater than 50–50 chance of answering correctly. Respondents have lower chance of getting the item correct when the item is above the respondent's proficiency. The Rasch model did not violate the assumptions of item response modeling that each subscale is unidimensional and higher scores are associated with higher proficiencies as the data fit the model sufficiently (Merritt 2010).

The Construct Map software (Kennedy et al. 2005) was used to calibrate items. All items (pretest, posttest, and embedded assessment) were calibrated together. Therefore, each student observation was treated as two different students. For example, a student's pretest is one student and their posttest is another "student." We were then able to anchor the difficulties generated for the entire set and look at each of the items separately. We then examined how students' models progressed in relationship to the instructional strategies of the unit.

Student Progress to a Particle Model of Matter

Table 6 details the mean and sample variances of the student ability estimates for the particle model of matter (PMM) variable. Logits are the unit of measure used by Rasch and represent the probability of a correct response, and the higher the logit number, the more likely students are to respond correctly to the items. This group of students starts out with a higher average ability estimate on the pretest than those in our overall study of student performance (Merritt 2010). The wide variance in student

Table 6 Means and variances of person ability estimates for the PMM progress variable ($N=122$)

Assessment	Mean (in logits)	Sample variance
Pretest	–0.54	0.80
AS1.1	0.82	3.39
AS5.2	1.03	2.75
AS15.1	1.27	3.79
Posttest	1.08	0.62

Table 7 Student proficiency estimate gains from each successive assessment

	Gain	*p*
Pre–AS1.1	1.36	<0.001
AS1.1–AS5.2	0.21	0.31
AS5.2–AS15.1	0.24	0.20
AS15.1–post	–0.19	0.26

results for the embedded assessments indicates the different models that students created for each assessment.

Students performed consistently better from the pretest to AS15.1. Gains in students' proficiency estimates are reported in Table 7, as well as results of paired-sample t-tests. There were significant gains from the pretest to AS1.1. There were gains from AS1.1 assessment to the AS15.1 assessment, but they were not significant. There is a slight (−0.19), but insignificant ($p = 0.26$), drop in performance from AS15.1 to the posttest. This drop may be explained because there is no scaffolding for the modeling items of the posttest.

The pretest and posttest separation reliabilities were satisfactory for the PMM progress variable ($r \geq 0.80$). However, those for the embedded assessments were less satisfactory ($r = 0.67$). These results were most likely due to the small sample size ($n = 122$). The embedded assessments also displayed a wide variance in student performance. These may be due to a number of factors, including teacher effects and fidelity to curriculum.

Another way of looking at students' progress from pretest to posttest is the Performance Map (Fig. 2). The Performance Map shows students' ability estimates over time. A Performance Map can be generated for a single student, for an entire class, or entire groups of students. Figure 2 shows the average progress for all students from pretest to posttest. Overall, this indicates that student conception of matter improved during instruction. Prior to instruction, the average student had a "mixed" model of matter, which means they represented and explained phenomena with matter as having both macroscopic and submicroscopic components. After the first lesson (AS1.1), the average student was now explaining phenomena with a "basic" model of matter which means they represented and explained phenomena with matter being composed of particles. However, students did not describe what these particles were. After Lesson 5 (AS5.2), more students are explaining phenomena with a "basic" model of matter. At this point in instruction, many students are now including motion and the concept of empty space in their model as they have learned these ideas in the lessons prior to the assessment. The final embedded assessment (AS15.1) shows that on average, students have progressed to a "complete" model of matter. At this point, students have been taught that the particles are atoms/molecules and have used their models to explain phase changes as well as that the atoms/molecules and their arrangement in different substances results in different properties. Just as the results show in Table 6, the average student had a "basic" model of matter.

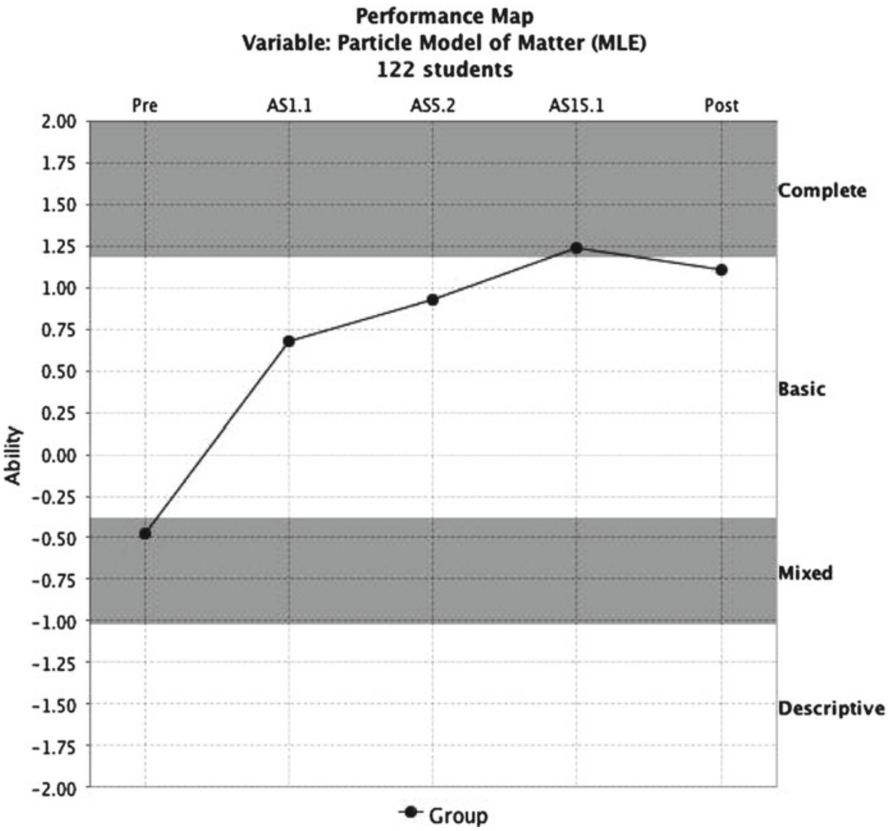


Fig. 2 Map of average student progress on the PMM progress variable

Student Development of a Particle Model of Matter

Through the development of the particle model of matter progress variable, we were able to track students' development of a particle model of matter during instruction. At the pretest, most students ranged from a descriptive to a basic model of mater. By the first embedded assessment (AS1.1), students displayed significant growth in performance (from pretest to AS1.1). AS1.1 occurs at the beginning of the unit, and results indicated that most students had either a mixed or basic model of matter. This growth could have occurred because of the discussions students have prior to and during creating their models. During this discussion, students had the opportunity to talk about how they thought odors are able to travel through the air. In addition, students were able to talk with peers as they created their models. Figure 3a shows Laura's initial model of smell. Laura shows odor as shaded lines, representing a descriptive model of matter.

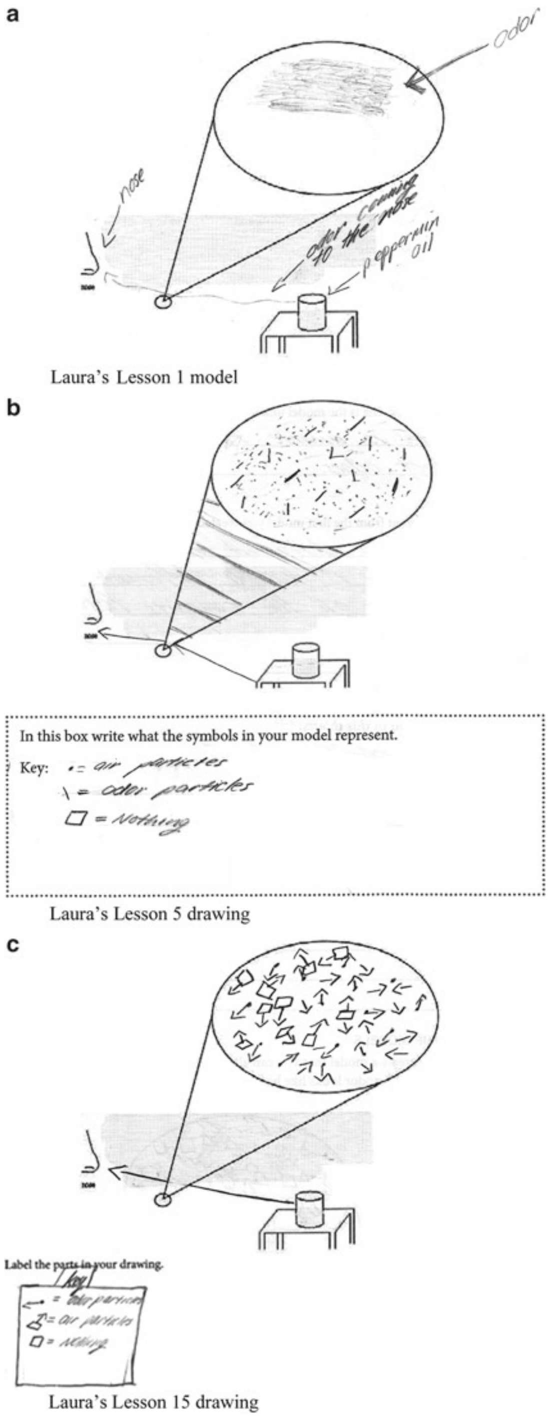


Fig. 3 Laura's drawing for how smell travels during instruction: (**a**) Lesson 1, (**b**) Lesson 5, and (**c**) Lesson 15

In the three lessons that follow, students investigated matter, defining matter as anything that has mass and takes up space. Students then grouped different materials as solids, liquids, and gases and characterize each of the different states of matter. Students also observed the melting and freezing of menthol to understand that heating and cooling can change matter from one state to another. The next set of instructional activities was key in helping students to gather evidence that matter is made up of tiny particles. Students studied the properties of gases by observing that air can be removed and added to a flask. Moreover, they use syringes filled with air to understand that gases can be expanded or compressed because there is empty space between the particles of a gas. Students created their own models of matter to explain these phenomena. Students were challenged to show how their models could account for the evidence (i.e., explain these various phenomena). Thus, these investigations were used as evidence for a particle model of matter.

Using student models, in Lesson 5, students were introduced to the idea that everything is made up of particles. They investigated the ability of an acid and a base to change the color of indicator paper without being dipped in the liquid. Through creation of models and discussions around the phenomenon and the models, students developed an understanding of evaporation and that the particles of the liquid are the same as those of the gas. Then, students were introduced to a different model, a computer simulation to explain how smells travel across a room before constructing their own models of smell. Students' models indicate that these instructional strategies helped students to further develop a particle view of matter. For example, Laura's model (see Fig. 3b) reflects the ideas that she gained from prior lessons. In her model of smell traveling, she now indicates that there are air particles and odor particles with and nothing between those particles. This is vastly different from Laura's first model of smell (Fig. 3a), which showed only odors as continuous. This also indicates that Laura has moved from a "descriptive" model of matter to a "basic particle" model of matter (see Table 2).

In the next learning set, students experienced phenomena to help them understand properties and phase changes on a molecular level. During these lessons, students learned about atoms and molecules. By the end of the second learning set, students should understand that the properties of different substances are the result of the different atoms in the molecules in that substance.

In the third learning set, students revisited phase changes. Students created models for phase changes on a molecular level. Students modeled how the substances appear in the different states as well as how heating and cooling changes the states of matter. For example, students examined whether gases move faster at higher temperatures by investigating how long it takes ammonia vapor to change indicator paper blue when a test tube containing drops of ammonia is in a warm versus cool water bath. Although there are several instructional strategies that occur between Lesson 5 and Lesson 15, it is difficult to pinpoint which of these have contributed most to student learning gains from Lesson 5 until Lesson 15. Since the unit was written with a particular sequence of learning performances and their associated learning activities, it can be postulated that this learning sequence helped students to develop a particle model of matter. Most students developed a "complete" model of matter at the end of the unit. For example, Laura (see Fig. 3c) has an even more sophisticated model of matter, as she now represents random movement of particles in her model.

Student performance, on average, dropped between AS15.1 and the posttest. AS15.1 occurs before a class review of all the major concepts students have learned. During this review students create models of phenomena before coming to a class consensus model that can explain all the phenomena that they have reviewed. Similar to the findings of McNeill et al. (2006), where they observed a drop in student performance between the end of instruction and the posttest for writing explanations because of the lack of scaffolding and peer-to-peer sharing that occurred during the unit, may also explain student performance on the posttest modeling items for this unit.

Conclusions and Implications

The particle nature of matter is a core idea of science (Smith et al. 2006; Stevens et al. 2009) that serves as the foundation for explaining a myriad of science phenomena including properties, phase change, and chemical reactions. Previous interview studies (Nakhleh et al. 2005; Novick and Nussbaum 1978; Stavy 1991) have outlined the difficulties students have with understanding particle theory and its related concepts. Our work shows that carefully sequenced curriculum materials that support students in using the scientific practice of modeling can help students develop an initial particle view of matter.

The scientific practice that served as the focus of the unit was modeling – an important and vital tool for helping students to understand abstract concepts such as the particle nature of matter (Harrison and Treagust 1998; Mikelskis-Seifert and Leisner 2005; Saari and Viiri 2003; Schwarz and White 2005). Research has suggested that students need to be introduced to modeling early in their school years (Grosslight et al. 1991; Harrison and Treagust 1998; Hestenes 1992; Justi and Gilbert 2002; MacKinnon 2003; Mikelskis-Seifert and Leisner 2005; Saari and Viiri 2003; Schwarz and White 2005; Vosniadou 1994). We designed the unit so that students would make observations through their investigations that would allow them to build more successive and appropriate models of the PMM over time based on evidence.

Studies have also suggested that students' understanding of the particle nature of matter would improve if a sequenced, developmental approach was taken to supporting students understanding of particle theory (Ben-Zvi et al. 1986; Harrison and Treagust 2002; Justi and Gilbert 2002; Kozma et al. 2000; Snir et al. 2003). This study showed that curriculum designed to allow students ideas to build over time with teachers who implement the unit helps students to do this. Our study found that this started with students' creation and critique of their own models to explain phenomena that account for their observations of phenomena. Results showed that as students gathered more evidence from phenomena, they were able to draw more sophisticated models, especially at the particle level. Learning progressions have been proposed as a means to address the need for curriculum and assessments that can help teachers improve their practice as well as to inform both students and teachers about students' performance. Wilson (2005) and Wilson and Sloan (2000) propose that one method for linking assessments to learning progressions is through the use of progress variables (Wilson 2009). Moreover, progress variables have been proposed as a method to tracking student performance during instruction (Wilson 2005, 2009). This study demonstrated that the PMM progress variable, developed for a curriculum unit designed to be coherent, can track student progress toward a PMM during instruction. Student performances on the embedded assessments indicated that students made gains in their proficiency as they experienced the unit, achieving higher levels of proficiency during instruction. Although average student performance dips to the "basic" level on the posttest, the results showed that students were able to develop a PMM by the end of the unit. It is important to realize that the performance on the posttest was not supported. Thus, the development of the progress variable provided the opportunity to track students' progress prior to, during, and after instruction. Furthermore, results showed that the instructional strategies helped students to develop a particle view of matter.

Scoring guides were developed for this study that aligned with the levels of the progress variable, which were delineated through the construct map. As the construct map also reflects the learning goals and instructional sequencing of the curriculum, it also points out the importance of embedded assessments tied to the learning goals of a curriculum (Kennedy et al. 2005). Therefore, the validated PMM progress variable could now be used by teacher and students to track student progress. Moreover, teachers could use the PMM progress variable to track students during instruction and provide feedback to students.

Results showed that students performed consistently better from pretest to the last lesson of the unit. Student performances on the embedded assessments indicate that students make significant gains in their proficiency as they experience the unit, achieving higher levels of proficiency. Thus, the development of this progress variable provided the opportunity to identify the range of models students created prior to and during instruction. Results show that the instructional strategies of the sixth grade IQWST chemistry unit help students develop a particle view of matter.

There were several limitations to this study. We anticipated that there would be some teacher effects as well as fidelity issues related to students' performance. During this study, we did not collect videos of instruction or interview the teachers about their experiences with the unit. This information could provide more insight into differences in student performance as they experience the unit as well as their performance on the posttest. Although this information was not collected, it does not affect the ability to track students understanding as they experience the unit. However, it does show that more work is needed in terms of both understanding fidelity to curriculum as well as documenting strategies teachers implement in supporting their students in progressing toward a particle view of matter.

Second, the embedded assessments consist of only two questions that are identical in content. Although having only two items does not limit the ability to determine estimation parameters for these items, having more items would provide better estimates of the construct. Moreover, there are several other embedded assessments that could also be utilized to better analyze students' particle view of matter in relationship to phase changes, states of matter, and properties of substances.

Finally, all the teachers that participated in the study did not return the embedded assessments as well as the pretests and posttests. Despite constant communications and reminders to send these items, many teachers did not send complete data. As a result, only three teachers returned complete materials. Although this was less than ideal, it did not inhibit our ability to track students understanding in three different locations.

In sum, a curriculum that is designed to help students to explain new phenomena through the practice of modeling with teacher who implement the curriculum using the intended practices can support students in developing a PMM. As students experienced the unit, results indicate that the particle model of matter progress variable could be used to track students' understanding during instruction. In addition, results show that students can develop a "complete" particle view of matter during instruction. Utilizing the PMM progress variable, most students moved from a "mixed" to a "basic" view of matter with a number of student reach the complete model by the posttest. This is reflected in students learning gains from pre- to posttest and in the increased sophistication of the models students created during instruction.

Now that the PMM progress variable has been validated, it provides the opportunity to return to the classroom to evaluate its use during instruction. The linking of instruction to assessment is vitally important to obtain a complete picture of how closely teachers are following the curriculum, what modifications they make to the curriculum, and how they utilize the embedded assessments to inform their practice, evaluate student progress, and provide feedback to students. Thus, teachers could be instructed to use the scoring guide to evaluate student progress to help them in understanding their students' progress as well as to provide feedback to students. The progress variable could also be used as evidence for learning progressions that span multiple grades. However, this is only one approach for supporting students in the development of a PMM. More work is needed to assess how other instructional strategies help students' progress to a PMM.

Acknowledgments This research was conducted as part of the Investigating and Questioning our World through Science and Technology (IQWST) project and the Developing an Empirically-Tested Learning Progression for the Transformation of Matter to Inform Curriculum supported in part by the National Science Foundation Grants ESI 0101780 and DRL-0822038, respectively. Any opinions expressed in this work are those of the authors and do not necessarily represent either those of the funding agency or the University of Michigan and Michigan State University.

Appendix

Lesson Descriptions and Learning Performances for the *How can I smell things from a distance?* Unit

	Lesson no.	Description	Learning performance
Learning set 1	1	Students smell odors coming from two jars, recognizing that the jar must be open in order to smell an object. During this investigation, students draw pictures and write descriptions that represent their understanding. Next, the teacher facilitates a discussion to help students think about (a) how odors travel and (b) how scientific models help them to understand and explain this phenomenon	Students construct initial models to help them explain how odors travel across a room Students describe one purpose of a scientific model
	2	Students measure the mass and volume of different substances, including an inflated/deflated ball to understand that odors and air have mass and occupy space (have volume) and conclude that anything with mass and volume can be called “matter”	Students describe air as occupying space (having volume) and having mass Students identify the relationship between the amount of a substance and the measured mass of that substance Students characterize things as matter (or not matter) based on whether they have mass and volume
	3	Students classify materials as solid, liquid, or gas. Students learn that matter can go through phase changes by observing the melting and cooling of menthol. As an optional activity, students can also observe the phase changes of water	Students identify and describe materials in three states of matter, using scientific terminology (solid, liquid, gas) Students describe and compare the characteristics of solids, liquids, and gases Students describe typical changes of states that occur when substances are heated or cooled Students provide examples of materials changing states

(continued)

(continued)

	Lesson no.	Description	Learning performance
	4	Students investigate the ability of air to be added and removed, expanded and compressed in closed systems, using their own models to explain them. Through the critique of their models, students begin to understand that the building blocks of matter are particles. Empty space between the particles explains addition, subtraction, compression, and expansion	Students construct and revise models to explain and account for all of the following phenomena: subtraction, addition, compression, and expansion of gas in a closed container
	5	Students develop an understanding that matter, in the gaseous state, contains particles that constantly move in linear motion by observing indicator paper changing color without being dipped in two different liquids. Students also view a simulation of odor traveling in a room with air. By the end of this lesson, the class develops a consensus model for the particle model of matter	Students construct models of the particle nature of gases Students use their models to explain why indicator paper changes color and how smell travels Students describe evaporation as particles of liquid changing phases to particles of gas without boiling
Learning set 2	6	Students observe and record the emission spectra of different gases. Through discussion of their data and modeling of different gases, students come to the idea that different materials have different properties; thus, we can distinguish among materials based on their properties	Students compare one substance to another, based on their properties
	7	Students are introduced to the elements of the periodic table and the physical properties of elements, by observing and investigating different elements. Students use their results to explain that the elements have different properties because they are made up of different types of atoms. Students are also introduced to fundamental concept of the atom – as a basic particle of all elements	Students compare several elements to one another, based on observable properties and uses Students define what an element is using the concept of atoms (and not particles)

(continued)

(continued)

Lesson no.	Description	Learning performance
8	Students create molecular models of oxygen, carbon dioxide, nitrogen, and water using gumdrops, Styrofoam balls, or other molecular modeling kits to represent atoms and molecules. The molecular models are then placed in a clear bag to represent air as a mixture of gases. The teacher facilitates discussions to help students understand these models and to introduce molecules as being composed of more than one atom that "stick" together and that different molecules make up different substances	Students use physical representations to explain the relationship between molecules and atoms Students identify a sample item as either a substance or a mixture on a molecular level
9	Students rotate through stations smelling different substances. Each station will include a 2-D image of the molecule. Students recognize the fact that the same atoms (C, H, O) can be in different arrangements and that these different arrangements make a new substance with new properties (in this lesson, a different odor)	Students explain that different smells are caused by different arrangements of atoms in a molecule, using molecular models
10	Students observe the time it takes ammonia vapors at different temperatures to reach indicator paper	Students predict how molecules move at different temperatures
	Students revisit the virtual simulation of air and odors in a room, manipulating temperature to show the difference in molecular movement at higher and lower temperatures	Students describe what happens to the molecules in a gas when it is cooled and heated Students construct models to demonstrate that molecules have different speeds at different temperatures Students explain why an odor moves faster at higher temperatures

(continued)

(continued)

Lesson no.	Description	Learning performance
11	Students observe the cooling and heating of a balloon placed in and removed from a dry ice bath. Students use the particle model to explain their observations. Finally, a mechanical model is used to demonstrate the relationship between temperature and volume in the heating and cooling of gases	Students describe what happens to the molecules in a gas when it is cooled and re-heated Students explain the relationship between temperature and volume of gases
12	Students observe the heating and cooling of bromine and create models of bromine in both the gas and liquid phase to help understand the process of evaporation. Then, students observe the evaporation of alcohol and water from two different surfaces to understand that different substances, which are composed of different molecules, have different evaporation rates. Third, a teacher demonstration of water boiling is used to explain the process of boiling and what happens as a liquid undergoes a phase change to gas. Students model the process of boiling to develop understanding of this process. Finally, students observe the process of condensation, through water condensing and evaporating in a bottle and the condensation of water on the outside of a plastic cup filled with ice water	Students explain phase changes from gases to liquids and liquids to gases at the molecular level
13	Students observe the expansion of water when it is heated and create physical models to explain their observations. Students then use their models to predict what happens when dye is added to hot and cold water. Students discuss whether their predictions match their observations and revise their models accordingly	Students describe the difference between liquids at different temperatures, including the fact that liquids expand upon heating Students explain the difference between liquids at different temperatures using a particle model

(continued)

(continued)

Lesson no.	Description	Learning performance
14	Students observe the phase change from a solid to a liquid by observing ice melting and through a teacher demonstration of melting an unscented, paraffin wax candle, creating models of solid and liquid water (or wax). Students observe sublimation using dry ice. Teacher reviews the menthol experiment (Lesson 3) and students create models of the molecules in the solid, liquid, and gaseous states	Students explain phase change from a solid to a liquid and from solid to a gas (sublimation), using the particle model Students explain different states of same substance, including in their explanations that the particles are the same but behave differently
15	Students revisit the models they created during Lessons 1 and 5 and create models of smell. The class reviews what they learn and develop a class consensus particle model. Then, students use their consensus model to address a real-world problem	Students evaluate models (compare and critique their models of odor) Students explain a related phenomenon, which is presented in a format of a short newspaper article, using the particle model Students create a poster/brochure suggesting a solution to a real-world problem

References

American Association for the Advancement of Science. (1993). *Benchmarks for science literacy*. New York: Oxford University Press.

Baker, S., & Talley, L. (1972). The relationship of visualization skills to achievement in freshman chemistry. *Journal of Chemical Education, 49*(11), 775–776.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education, 63*, 64–66.

Corcoran, T., Mosher, F. A., & Rogat, A. (2009). *Learning progressions in science: An evidence-based approach to reform* (Center on continuous instructional improvement). New York: Teachers College, Columbia University.

Davis, F., Davis, R. A., & Sarquis, M. (2006). *Modern chemistry*. Austin: Holt, Rinehart and Winston.

Davis, E. A., & Krajcik, J. (2005). Designing educative curriculum materials to promote teacher learning. *Educational Researcher, 34*(3), 3–14.

deVos, W., & Verdonk, A. H. (1996). The particulate nature of matter in science education and in science. *Journal of Research in Science Teaching, 33*, 557–664.

Driver, R., Guesne, E., & Tiberghein, A. (1985). *Children's ideas in science*. Philadelphia: Open University Press.

Driver, R., Squires, A., Rushworth, P., & Wood-Robinson, V. (1994). *Making sense of secondary science: Research into children's ideas*. New York: Routledge.

Ferguson, R., & Bodner, G. (2006). *Misconceptions held by chemistry majors while taking organic chemistry*. Paper presented at the 2006 annual meeting of the National Association of Research in Science Teaching, San Francisco.

Grosslight, L., Unger, C., Jay, E., & Smith, C. L. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 29*, 799–822.

Harrison, A., & Treagust, D. (1996). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. *Science Education, 80*, 509–534.

Harrison, A., & Treagust, D. (1998). Modelling in science lessons: Are there better ways to learn with models? *School Science and Mathematics, 98*, 420–429.

Harrison, A., & Treagust, D. (2002). The particulate nature of matter: Challenges in understanding the submicroscopic world. In J. K. Gilbert et al. (Eds.), *Chemical education: Towards research-based practice* (pp. 189–212). Boston: Kluwer Academic Publishers.

Hestenes, D. (1992). Modeling games in the Newtonian World. *American Journal of Physics, 60*(8), 732–748.

Johnson, P. (1998). Progression in children's understanding of a 'basic' particle theory: A longitudinal study. *International Journal of Science Education, 20*(4), 393–412.

Johnson, P., & Papageorgiou, G. (2010). Rethinking the introduction of particle theory: A substance-based framework. *Journal of Research in Science Teaching, 47*(2), 130–150.

Justi, R., & Gilbert, J. (2002). Models and modeling in chemical education. In J. K. Gilbert et al. (Eds.), *Chemical education: Towards research-based practice* (pp. 47–68). Boston: Kluwer Academic Publishers.

Kennedy, C. A., Wison, M., & Draney, K. (2005). *Construct map. Computer program*. Berkeley: Berkeley Evaluations and Assessment Research Center, University of California.

Kennedy, C., Brown, J., Draney, K., & Wilson, M. (2006). *Using progress variables and embedded assessment to improve teaching and learning*. Paper presented at the annual meeting of the American Educational Research Association, San Francisco.

Kozma, R., Chin, E., Russell, J., & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning. *The Journal of the Learning Sciences, 9*(2), 105–143.

Krajcik, J. S. (1991). Developing students' understandings of chemical concepts. In S. H. Glynn, R. H. Yeany, & B. K. Britton (Eds.), *The psychology of learning science*. Hillsdale: Erlbaum.

Krajcik, J. S., & Blumenfeld, P. (2006). Project-based learning. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences*. New York: Cambridge University Press.

Krajcik, J., McNeill, K., & Reiser, B. (2008). Learning-goals-driven design model: Developing curriculum materials that align with national standards and incorporate project-based pedagogy. *Science Education, 92*(1), 1–32.

Krajcik, J. S., Reiser, B. J., Sutherland, L. M., & Fortus, D. (2012). *Investigating and questioning our world through science and technology (IQWST)*. New York: Sangari Global Education.

Lee, O., Eichinger, D., Anderson, C. W., Berheimer, G., & Blakeslee, T. (1993). Changing middle school students' conceptions of matter and molecules. *Journal of Research in Science Teaching, 30*(3), 249–270.

Liu, X., & Lesniak, K. (2006). Progression in children's understanding of the matter concept from elementary to high school. *Journal of Research in Science Teaching, 43*(3), 320–347.

MacKinnon, G. (2003). Why models sometimes fail. *Journal of College Science Teaching, 32*(7), 430–433.

Margel, H., Eylon, B., & Scherz, Z. (2008). A longitudinal study of junior high school students' conceptions of structure of materials. *Journal of Research in Science Teaching, 45*(1), 132–152.

McNeill, K. L., Lizotte, D. J., Krajcik, J., & Marx, R. W. (2006). Supporting students' construction of scientific explanations by fading scaffolds in instructional materials. *The Journal of the Learning Sciences, 15*(2), 153–191.

Merritt, J. (2010). Tracking students' understanding of the particle nature of matter. Unpublished doctoral dissertation, University of Michigan, Ann Arbor.

Merritt, J., Schwartz, Y., Sutherland, L. M., & Krajcik, J. (2012). How can I smell things from a distance? In J. S. Krajcik, B. J. Reiser, L. M. Sutherland, & D. Fortus (Eds.), *Investigating our world through science and technology (IQWST)*. New York: Sangari Global Education.

Mikelskis-Seifert, S., & Leisner, A. (2005). Investigation of effects and stability in teaching model competence. In K. Boersma et al. (Eds.), *Research and the quality of science education* (pp. 337–351). New York: Kluwer Academic Publishers.

Nakhleh, M. B. (1992). Why some students don't learn chemistry: Chemical misconceptions. *Journal of Chemical Education, 69*(3), 191–196.

Nakhleh, M. B., Samarapungavan, A., & Saglam, Y. (2005). Middle school students' beliefs about matter. *Journal of Research in Science Teaching, 42*, 581–612.

National Research Council. (1996). *National science education standards*. Washington, DC: National Academy Press.

National Research Council. (2001). *Knowing what students know: The science and design of educational assessment.* Committee on the Foundations of Assessment. J. Pelligrino, N. Chudowsky, & R. Glaser (Eds.). Board on Testing and Assessment, Center for Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

National Research Council. (2007). *Taking science to school: Learning and teaching science in grades K-8*. Committee on Science Learning, Kindergarten through Eighth Grade. R. A. Duschl, H. A. Schweingruber, & A. W. Shouse (Eds.). Board on Science Education, Center for Education. Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas.* Committee on a conceptual framework for New K-12 Science Education Standards. Board on Science Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

Novick, S., & Nussbaum, J. (1978). Junior high school pupils' understanding of the particulate nature of matter: An interview study. *Science Education, 62*, 273–281.

Renstrom, L., Andersson, B., & Marton, F. (1990). Students' conceptions of matter. *Journal of Educational Psychology, 82*(3), 555–569.

Saari, H., & Viiri, J. (2003). A research-based teaching sequence for teaching the concept of modeling to seventh-grade students. *International Journal of Science Education, 25*(11), 1333–1352.

Schwarz, C., Reiser, B., Davis, E., Kenyon, L., Acher, A., Fortus, D., et al. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(1), 232–254.

Schwarz, C., & White, B. (2005). Metamodeling knowledge: Developing students' understanding of scientific modeling. *Cognition and Instruction, 23*, 165–205.

Smith, C., Wiser, M., Anderson, C., & Krajcik, J. (2006). Implications of research on children's learning for standards and assessment: A proposed learning progression for matter and the atomic-molecular theory. *Measurement, 14*(1&2), 1–98.

Snir, J., Smith, C. L., & Raz, G. (2003). Linking phenomena with competing underlying models: A software tool for introducing students to the particulate model of matter. *Science Education, 87*(6), 794–830.

Stavy, R. (1991). Children's ideas about matter. *School Science and Curriculum, 91*, 240–244.

Stevens, S. Y., Sutherland, L. M., & Krajcik, J. S. (2009). *Big ideas of nanoscale science and engineering*. Arlington: NSTA press.

Stevens, S. Y., Delgado, C., & Krajcik, J. (2010). Developing a hypothetical multi-dimensional learning progression for the nature of matter. *Journal of Research in Science Teaching, 47*(6), 687–715.

Taber, K. S. (2003). The atom in the chemistry curriculum: Fundamental concept, teaching model or epistemological obstacle? *Foundations of Chemistry, 5*(1), 43–84.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*, 45–69.

Wilson, M. (2005). *Constructing measures: An item response modeling approach*. Mahwah: Lawrence Erlbaum Associates.
Wilson, M. (2009). Measuring progressions: Assessment structures underlying a learning progression. *Journal of Research in Science Teaching, 46*(6), 716–730.
Wilson, M., & Sloan, K. (2000). From principles to practice: An embedded assessment system. *Applied Measurement in Education, 13*, 181–208.

How Students' Understanding of Particle Theory Develops: A Learning Progression

Philip Johnson

Introduction

Research stretching back many decades would suggest that students find the particulate nature of matter difficult to grasp. Several comprehensive reviews of this large body of work exist (e.g. Andersson 1986; Garnett et al. 1995; Harrison and Treagust 2002; Krnel et al. 1998; Liu 2001; Smith et al. 2004; Wiser and Smith 2008), and there is no attempt to replicate these here. The main focus of this chapter is on students' understanding of a 'basic' particle model, which refers in general to the particles of a substance (e.g. copper particles, water particles, salt particles) without differentiating between atoms, molecules and ions. Many students at all ages do seem to struggle with particle ideas, but some do succeed.

A longitudinal, interview-based study on a cohort of students ($n=33$) moving from age 11 to 14 has given evidence of understanding developing along a progression (Johnson 1998). Data on students' understanding of a 'basic' particle model were collected as part of a wider study on the concept of a substance. From holding a continuous view of matter before instruction (i.e. no notions of particles in the sense of the particle theory), a sequence of qualitatively different models concerning the relationship between particles and the substance emerged:

Model A: The particles are in the continuous substance.
Model B: The particles are the substance but have macroscopic character.
Model C: The particles are the substance, but they do not have macroscopic character.

In response to a question about particles, students holding Model A can draw seemingly acceptable particle diagrams, but when asked to indicate the substance, they shade in the spaces between the particles. For them, the particles are extra things embedded within the continuous substance (see Fig. 1).

P. Johnson (✉)
School of Education, Durham University, Durham, UK
e-mail: p.m.johnson@durham.ac.uk

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_3,

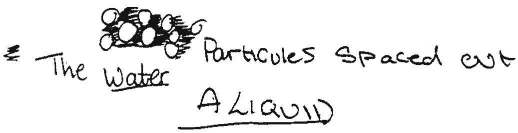


Fig. 1 Model A response for liquid water (From Johnson 1998, p. 400: Taylor and Francis, http//www.tandfonline.com)

A more refined form of Model A is to show the substance as a coating around each particle. This seems to be moving closer to Model B where there is no distinction between the particles and the substance: the particles are viewed, literally, as being very small pieces/amounts of the substance and have the macroscopic character of the substance. Like Model A, Model B spans a range of development. In a more primitive form, macroscopic behaviour is explained by the behaviour of individual particles, entirely. For example, individual particles melt. A more sophisticated version explains different states for a particular substance in terms of changes in particle movement and spacing. However, individual particles of different substances are still thought to have the macroscopic properties of their room temperature states.

If the particles are the substance, it follows that there is nothing (no substance) between the particles. Most of the students in the Model B category seemed happy to accept this logic, but some would say 'air'. However, exactly what is meant by 'air' is not always clear (Johnson and Gott 1996), and 'air' does not necessarily mean matter in the scientific sense. The key distinction between Models A and B is that the particles are the substance in the latter but not the former. Students holding Model C appreciate that the characteristic properties of the three states are explained by the collective behaviour of the particles, entirely, and so the 'physical' nature of individual particles is not at issue. Single particles do not have a state and indeed it is difficult to say what they are like since they are not like anything we know.

The forces between particles and their intrinsic motion (i.e. that particles are always moving in some way) were other aspects overlaying the models. About two thirds of the students mentioned attractions between particles in at least one of the interviews. Here there was a distinction between those that seemed to view the strength of attraction as being a consequence of the room temperature state and those understanding that the room temperature state was determined by the ability of the particles to attract to each other. Cases of the former arose with students holding either Models A or B and the latter with students holding Models B or C. Overall, students were happy to talk about the movement of particles associated with the three states. For Model A, the movement is determined by the state of the continuous matter: thus, in a solid they are stuck, in a liquid they can move around and in a gas they have much more freedom. In relation to forces, the space-filling substance acts as 'glue' of varying strengths. Across all models the intrinsic nature of the motion seemed to be readily accepted for the gas state. However, for the liquid state there was a tendency to think in terms of a potential to move if acted upon in some way (e.g. stirring). Although most students could predict a crystal of sugar would dissolve in water without stirring, not one invoked ideas of intrinsic motion to explain why. Even those who spoke enthusiastically about the moving particles of the liquid state could not make the connection. The interviews did not focus on intrinsic motion and the solid state.

After the initial instruction, one student had not engaged with particle ideas in any way. The rest entered at either Models A or B and then moved along the sequence of A to B to C at differing rates in response to further teaching. At the end of the third year of the study, just under half had reached Model C. The interview sample ($n=33$) was drawn from the whole of a year cohort ($n=147$, in six classes), and a number of different teachers contributed to the teaching over the 3 years. However, all classes in each year had followed the same instructional units and the path of the students' development could simply be a reflection of this and have no wider significance. Nevertheless, the kinds of responses are similar to those reported by other studies. Indeed, based on a thorough analysis of the literature, where the bulk of studies have been cross-sectional, Talanquer (2009) has proposed a learning progression for the structure of matter that is consistent with the findings of the longitudinal study.

Talanquer (2009) identifies four specific dimensions along which there seem to be common paths of development: structure, properties, dynamics and interactions. 'Structure' captures the change from a continuous view of matter through 'granularity' (small pieces or embedded particles of some generic kind) to 'corpuscularity' (particles of a distinctive type are the matter). The 'properties' dimension moves from 'inheritance' (macroscopic properties are transferred to the particles) to 'emergence' (properties emerge from the interactions of particles). Under 'properties', Talanquer also notes 'substantialism' where properties such as taste and smell are thought to be quasi-material entities in themselves which are mixed in with the sample in question. It is suggested that this evolves into 'elementalism' (the properties of chemical elements are inherited by compounds) before 'emergence' is reached. 'Dynamics' starts with a static view of particles and finishes with a full appreciation that motion is intrinsic. On route are the notions that particles only move when forced to do so ('causal-dynamic') followed by continuous motion linked to perceptual features such as temperature and fluidity ('contingent-dynamic'). For 'contingent-dynamic', the higher the temperature or more fluid-like a material (liquid/gas), the more likely the particles are thought to be moving. Finally, the 'interactions' dimension begins with the idea that interactions only take place when particles are in contact ('contact-interactive') such as for the solid state. Next is contingent-interactive where the strengths of forces depend on the temperature (they weaken as temperature increases) and the state (they become weaker to the point of disappearing from solid to liquid to gas). The idea of intrinsic forces which only depend on distance ('intrinsic-interactive') is noted as seeming to be especially challenging.

Together, Talanquer's 'structure' and 'properties' dimensions (omitting 'substantialism') correspond to a progression from a continuous view of matter through the Models A to B to C as defined earlier. Responses in keeping with either Model A or B are usually regarded as misconceptions, and their prevalence in research studies is the evidence for why the particle theory is considered to be so difficult. If Models A and B are stages in a progression towards understanding the science view (Model C), this would cast the situation in a more positive light. A feel for how far Models A and B are along a possible road to C would inform the picture. More widely, there is recent attention in the literature to the prospect of learning progressions in science domains informing curriculum design (e.g. Duncan and Hmelo-Silver 2009; National Research Council (NRC) 2007).

This chapter reports the findings from a large-scale, cross-sectional study to test the hypothesis of a learning progression for the basic particle model. They form part of a wider study exploring students' understanding of the concept of a substance (as did the Author's previous longitudinal study), covering the identity of substances, changes of state, mixing and chemical change (Johnson and Tymms 2011). A computer-based assessment instrument, using fixed-response items, was developed, and Rasch modelling was used to explore the data for evidence of a learning progression (NRC 2001; Sadler 2000).

The Rasch Model

The Rasch model is based on the notion of a continuous variable (trait), where the 'abilities' of persons and the 'difficulties' of items in relation to the variable can be measured on the same interval scale (Wright and Stone 1979). The model uses the difference between person ability and item difficulty to predict the probability of a person succeeding on an item (see Fig. 2). The probability is 0.5 when the difference is zero. 'Statistics can be computed for each item and each student to show how well they fit the model, individually. There are two kinds of misfitting behavior; underfit and overfit. Underfit for an item is when ability is a poor predictor of success: a plot of observed success against ability-difficulty is more of a horizontal line rather than the ogive of Fig. 2. Overfit for an item is when ability is too good a

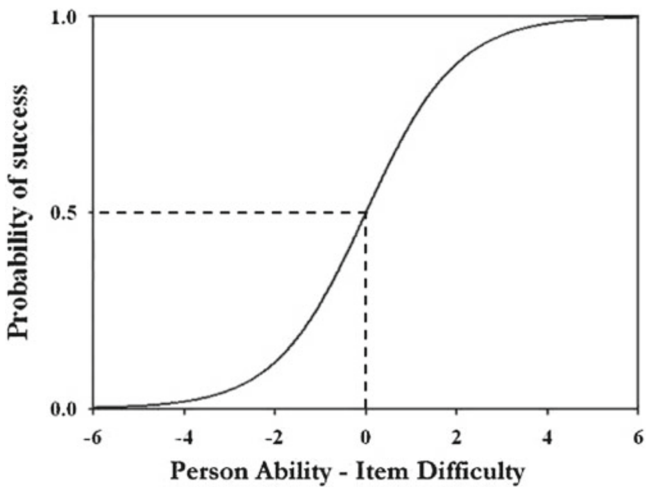


Fig. 2 The Rasch model response ogive (From Johnson and Tymms 2011, p. 852)

predictor of success: a plot of observed success against ability-difficulty is more step-like than the ogive. Students with ability below item difficulty exhibit less chance of success than expected and students with ability above difficulty exhibit greater chance than expected. Similarly, a person could be underfitting or overfitting' (Johnson and Tymms 2011, p. 851).

A data set conforming to the Rasch model indicates the items are measuring the abilities of the persons on a variable. 'If those items represent the understanding of certain ideas, the order of difficulty can be inferred to represent the order in which the understanding of the ideas is achieved; *i.e.*, a learning progression' (Johnson and Tymms 2011, p. 852).

Methodology

Item Development

Item construction was informed by the research literature (distracter options were based on likely misconceptions) and iterative trialling. During the trials, data were collected using individual interviews ($n=52$) and from classes sitting tests (number of students = 747). Most of the interviewees were in Years 7–9 (ages 11–14) with a few from older year groups (Years 10 and 11). The interview sample drew on seven schools, the students having been selected by teachers to represent the range of abilities within a school. The classes were an opportunistic sample covering all abilities, but biased in numbers towards higher achieving students. Samples from higher achieving schools tended to be larger, and where students were in stratified classes according to ability within a school, there were more higher ability classes than lower ability classes (and higher classes tend to be larger than lower classes). In total, 19 schools were involved in the development of items. These schools spanned a wide spectrum of socioeconomic backgrounds and achievement in high-stakes national assessments.

The interviews, which explored students' interpretations of wording and images and their reasons for selecting or not selecting options, were very useful and led to many alterations. For example, there was a preoccupation with the spacing between particles in many students' thinking. Figure 3a shows the first draft of an item on the relationship between the particles and the substance for the liquid state. It became clear that a number of students were choosing the first option because they thought that best showed the spacing between particles in liquid water and had not paid attention to the labelling which showed particles in continuous water (Model A). A second version showed the same spacing between particles in all options but some students still looked for a difference as their strategy for selecting an answer. The final version (Fig. 3b) states that the spacing is the same in all options.

An indication of the effect of the change is given in Table 1, which shows the percentage frequencies of option choices for the first version in class trials and the final version in the main data collection (see later for sample details). Despite

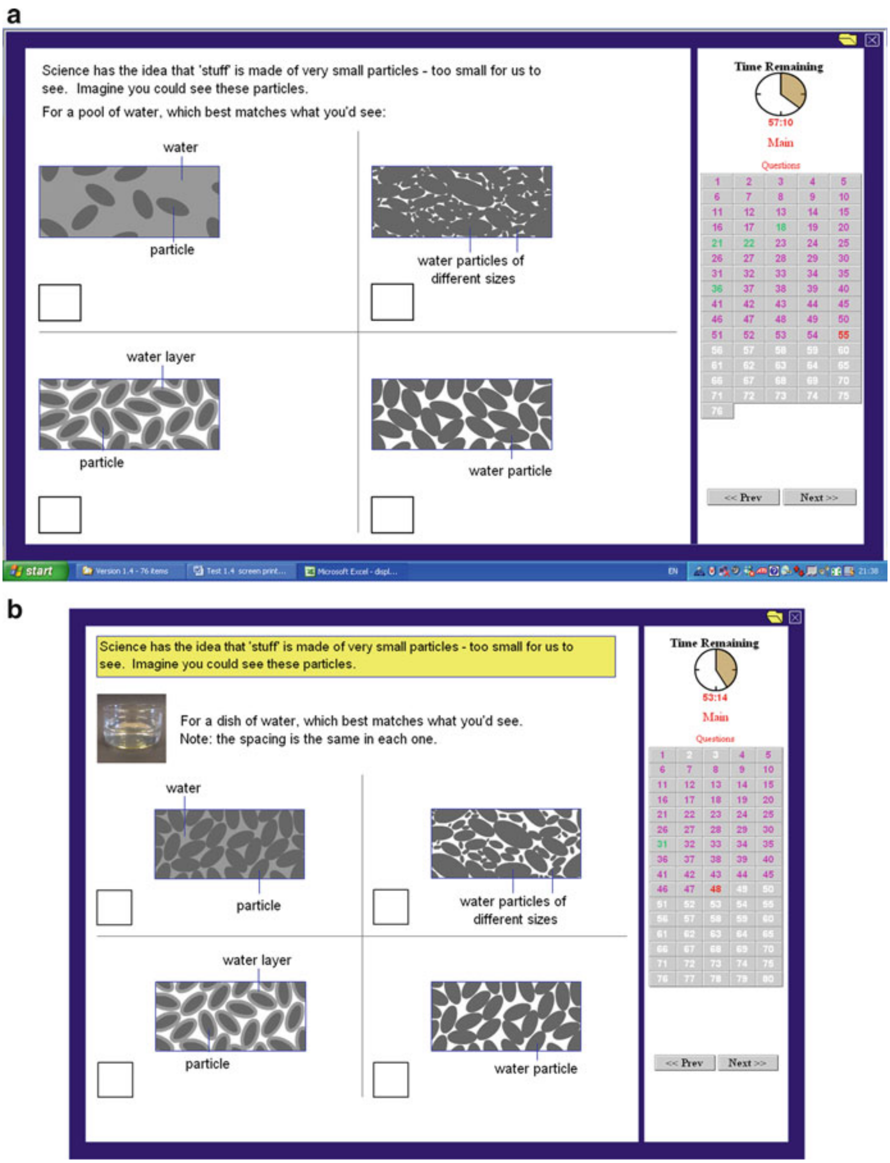


Fig. 3 (**a**) Pilot version. (**b**) Final version

their very different sizes, there is a reason to assume the samples draw on similar profiles of abilities (their mean abilities are above average). If so, it seems that the different spacing could entice some students away from choosing the correct option (D). That some interviewed students were distracted by differences in spacing is unquestionable.

Table 1 Percentage response frequencies for Fig. 3a, b

Option	Percentage response frequency	
	Figure 3a ($n=131$)	Figure 3b ($n=4,600$)
A	30	14
B	15	19
C	14	10
D	*42*	*55*

The interviews also revealed the importance of maintaining parity between options in terms of content and the use of what students see as key words (Sadler 2000). For example, the options and percentage response frequencies for two versions of an item asking 'which best describes' a beaker of water (shown in a photograph) are given below.

		Percentage response frequency
Pilot		$n=148$
A	It is made of particles which are runny – like tiny drops of water	26
B	There are particles which can move around in the water	53
C	It is made of particles which are not like little bits of water	*17*
D	It does not have any particles	3
Final		$n=4,600$
A	It is made of particles which are runny-like tiny drops of liquid	31
B	There are particles dotted about surrounded by liquid	32
C	It is made of particles which are not like little bits of water	*32*
D	It does not have any particles	3

With the first version, some students were selecting Option B because this was the only one that mentioned movement and were not necessarily taking in the context of that movement (Model A). The amended item makes no mention of movement in any of the options (and also specifies the water as liquid). Comparing the choices for the two versions suggests the mention of movement in the initial version drew some students away from the correct answer.

The number of distracters per item depended on the number of alternative plausible notions and varied from 2 to 6 with most either 3 or 4. Where appropriate, the rubric asked students to select the 'best' option (as in the examples above) to acknowledge there might not be an exact match to their thinking amongst the distracters – if they didn't hold the science view.

Aspects Addressed

The particle model comprises a set of ideas which work together, and, to the extent that it is possible, items were designed to address particular aspects of the model. These aspects and the number of items per aspect are shown in Table 2.

Table 2 Aspects addressed by the items

Aspect addressed by item	Number of items
The relationship between 'basic' particles and the substance	7
The nature of individual particles	5
The intrinsic motion of particles	7
The spacing of the particles (liquid state)	1
The use of a basic particle model to explain physical phenomena	9
Using ideas of atoms	9

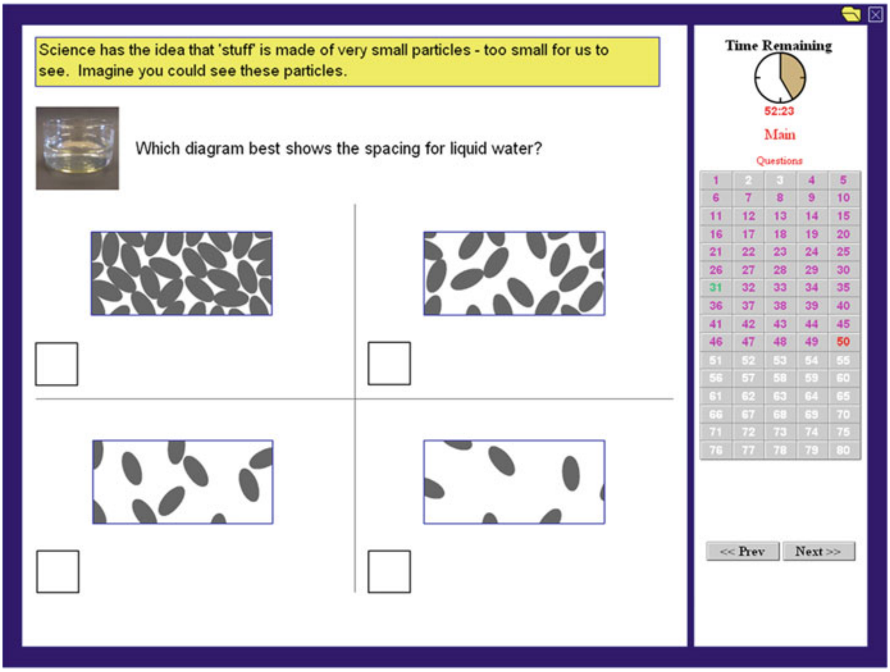


Fig. 4 An item on the spacing in the liquid state

Figure 3b is an example of an item exploring the relationship between 'basic' particles and the substance. Others looked at the solid and gas states, and still others more specifically on what was between the particles. The item above on which best describes water is an example of one which focuses more on the nature of individual particles.

Intrinsic motion was addressed in two ways. Some items displayed arrays of particles moving variously or not for the different states. Other items showed animated options of one particle either 'still but could move', 'shaking on the spot', 'moving around a little' or 'moving around a lot'.

Only one item looked directly at the spacing for the liquid state (Fig. 4).

However, spacing was also involved in some items to do with explaining physical phenomena. For example, an item to explain melting offered the following options (photographs showed a sample of wax before and after melting):

A. The particles move apart.
B. The wax around the particles melts.
C. Solid particles (hard) change to liquid particles (runny).
D. The particles start to move about from place to place, keeping close together.

Options A and D are juxtaposed to force a decision between a change in spacing or change in movement as the key factor explaining the difference between solid and liquid. Other items, most using particle diagrams, looked at explaining boiling, evaporation and dissolving (solid and gas state solutes). Ideas of forces between particles were addressed in items on different melting points, different rates of evaporation for different substances and hardness.

Table 2 also shows nine items that went beyond 'basic' particles and used ideas of atoms. One item offered the following two options for the best description of water:

A. It is one substance made of hydrogen and oxygen atoms.
B. It is a mixture of two substances, hydrogen and oxygen.

Other items showed molecular atom diagrams to represent changes of state, mixing, separation and chemical change. Two items also depicted chemical changes involving giant structures.

Students' understanding of properties such as smell and taste were not addressed since these rely on appreciating the role of our sense receptors and the brain in creating the sensations. Individual particles do not have a smell or taste in the way they have mass, energy or forces of interactions – there are just arbitrary shapes and sizes which fit receptors. The overall scope of the study was judged to be wide enough as it was.

The Instrument

Figure 5 shows how the 38 particle model items were distributed across three tests, one for Year 7, one for Year 8 and one for Year 9 and above (named Tests A, B and C, respectively). The numbers of items per test were constrained by the need to accommodate items addressing other ideas relating to the concept of a substance (the total numbers of items per test in the wider study are shown in parentheses in Fig. 5) and to keep the overall test completion times to within reasonable bounds (around 45 min). For the particle model items, a kernel of 11 items was assigned to each test. These items covered all of the aspects in Table 2 except 'atoms' for Year 7 (four 'relationship', two 'nature', one 'spacing', one 'motion' and three 'basic explain'). Three items were common to Tests A and B (covering 'nature', 'motion' and 'basic explain'). Three items, all on 'atoms', were common to Tests B and C. Nine items were only assigned to Test A (three 'relationship', five 'motion' and one 'basic

Test	Number of items: Kernel through all tests	Common to two tests		In one test			Total
A for Y7	11 (37)	3 (13)		9 (30)			24 (80)
B for Y8			3 (5)		3 (21)		20 (76)
C for Y9 and Y10						9 (34)	23 (76)

Fig. 5 The instrument design

explain'), three were only in Test B (one 'nature' and two 'atoms') and nine were only in Test C (5 'basic explain' and 4 'atoms').

The kernel items and those common to pairs of tests covered the range of difficulty and allowed for test equating and the comparison of subsamples. Placement decisions for items were guided by the students' likely curricular experiences according to the English National Curriculum. It should also be noted that the development phase also involved consultation with teachers during feedback of results. Overall, students were not being asked about unfamiliar content. For the items only appearing in one test, those in A tended to be easier and those in C more difficult.

Participants

Data were gathered in two batches. The first batch was collected from 20 schools (out of 200 who were approached) at the end of the academic year in June/July 2007. The data were collected at a distance in that the software was run on school IT networks under the supervision of school staff. It was requested that students completed the tests individually. There was considerable variation in the numbers of students per school and the relative numbers per year group in each school, but overall around one thousand students took each test (Table 3). The schools were drawn from the Middle Years Information System (MidYIS) database at Durham University's Curriculum Evaluation and Management (CEM) Centre (MidYIS 2011). Just over 2,000 secondary schools are in the database, and it constitutes a good representation of the English school population. When students enter Year 7, they take standardised tests across a range of areas. A student's total (MidYIS) score can be regarded as an overall indication of academic ability. The MidYIS scores were available for most of the students, and these showed the Years 7, 8 and 9 samples to be very similar. Each was fairly normally distributed but around a mean that was about one standard deviation above the national mean (standardised score means were 112, 114 and 114, respectively).

Table 3 First batch of data collected from 20 MidYIS schools

Year group and number of students taking a test			
Y7 on Test A	Y8 on Test B	Y9 on Test C	Y10 on Test C
1,212	1,048	917	114

Table 4 Second batch of data gathered from ten local schools

Numbers of students by Year group and test (total = 1,333)						
Y7	Y8		Y9			Y10
Test A	Test A	Test B	Test A	Test B	Test C	Test C
283	312	231	34	329	112	32

The second batch was collected from ten further schools between February 2008 and June 2008 (Table 4). Tests were not strictly aligned to year groups since in most cases they were being taken midyear. The bulk of these data were gathered by the Author in local schools using a class set of laptops. It was gratifying to see the students become quickly absorbed with the tests. However, a few in some classes ran through the items at speeds not consistent with careful thought. Overall, the schools in the two batches span a wide range of types, socioeconomic backgrounds and geographical areas.

Results

Rasch Analysis

The particle model items were subjected to Rasch modelling together with the items addressing other ideas relating to the concept of a substance. Since Rasch modelling uses the difference between ability and difficulty, the measurement of person ability does not depend on which items are attempted, and the measurement of item difficulty does not depend on which persons answer the items (though standard error reduces where ability matches difficulty). Therefore, all of the items in Tests A, B and C (see Fig. 5) and all students' responses in Batches 1 and 2 (Tables 3 and 4) could be combined to make one data set which was analysed using Winsteps, version 3.59 (Linacre 2005). Within this analysis, a few of the items were double scored. For example, Fig. 3b was scored once with Options B and D as correct to identify those students viewing the particles as being the substance and then again with just Option D as correct to distinguish those also regarding the particles as being all the same (of whatever nature). In effect, this scoring is equivalent to using a partial credit Rasch model (Bond and Fox 2007). The overall analysis gave an item reliability of 1.00 and a person reliability coefficient of 0.82 (equivalent to Cronbach's alpha). These statistics are very satisfactory and indicate there are enough items to estimate the student abilities and enough students to estimate the item difficulties. In relation to the fit statistics of individual items and persons, overfit (where prediction is too good) is of less concern than underfit (where there is poor prediction) (Bond and Fox 2007). Therefore, here we will only concern ourselves with underfit.

The individual person fit statistics indicate around 6 % of the students were underfitting. For Batch 2, the author had witnessed some students not giving the items proper consideration and this probably occurred with Batch 1 as well. Such an approach would show up in the Rasch model as underfitting person behaviour. Therefore, to gain a better assessment of the items, the data were reanalysed after removing the underfitting students. In practice, it made little difference.

Measures of item difficulty should not depend on which persons answer the items. The invariance of item difficulties with respect to MidYIS ability, year group and gender was investigated with the Batch 1 data. For MidYIS ability, for each test, upper and lower quartiles of students taking the test were identified using the MidYIS scores and the item difficulties were calibrated separately on the two subsamples (again using all items). Plots of the item difficulties calibrated on the upper quartile against those calibrated on the lower quartile showed a high correlation. For the particle model items only, correlation coefficients of 0.95, 0.91 and 0.69 emerged for Tests A, B and C, respectively. (For all items in each test, the corresponding correlations were 0.95, 0.85 and 0.80.) In each case, it must be noted that the upper and lower quartiles largely comprised of students from different sets of schools. Therefore, the invariance is being tested across a combination of MidYIS ability and schooling and the correlations are the more remarkable for that.

Since the Batch 1 data had been collected at the end of the academic year, the common items allowed invariance across year groups to be explored. For the 15 particle items common to Tests A and B, the plot of item difficulties calibrated on Year 7 students against those calibrated on Year 8 students has a correlation coefficient 0.99. For the 14 items common to Year 8 (Test B) and Year 9 (Test C), the correlation is 0.93, and for the 11 items common to Year 7 and Year 9, the correlation is 0.95. Using both batches of data, item difficulties calibrated by gender are almost identical.

Although some items were underfitting, overall, the data of the wider study show a good fit to the Rasch model (for a more detailed account the reader is referred to Johnson and Tymms 2011). This suggests a variable relating to the concept of a substance and that the particle model items belong to that variable. We will now consider what the particle items tell us about the development of students' understanding of the particle model.

Underfitting Items

One of the particle model items exhibited significant underfitting behaviour. 'Ability' on the 'substance' variable, as estimated by responses to all of the items, was not a good predictor of success on this particular item. Of course, this could

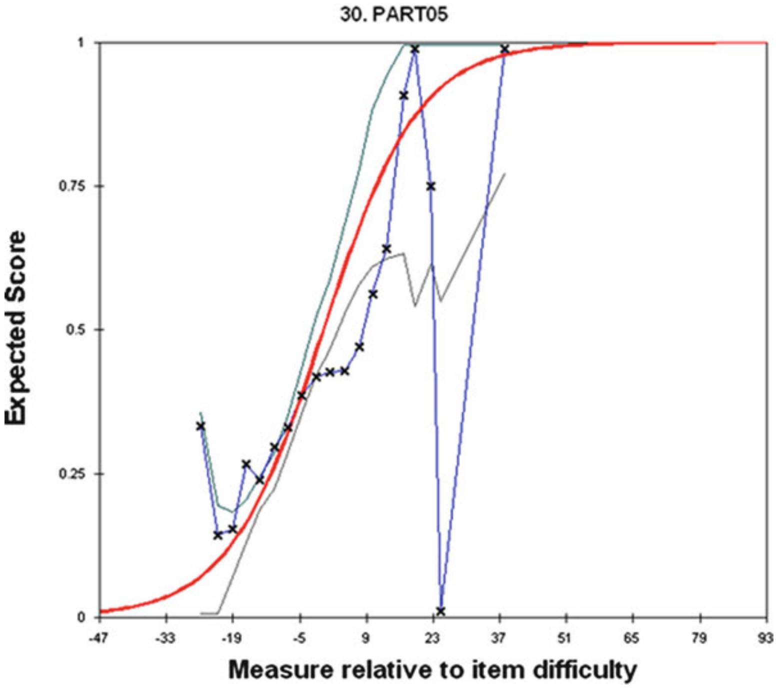


Fig. 6 Observed vs. expected probability of success for item on liquid spacing (Fig. 4)

simply be a poorly constructed item which is open to too many interpretations. On the other hand, it could be hitting a pocket of confusion that persists despite overall progress. There is reason to suppose the latter explanation. The item was the one on liquid state spacing (Fig. 4). Figure 6 gives the observed success rate (the plotted points) set against the expected ogive (the faint outer lines are the error limits). As well as some lucky guessing at the lower end, the observed success rate is markedly less than expected amongst the higher ability students. This is consistent with the dominance of an incorrect view of liquid state spacing in some students' thinking, noted earlier. These higher ability students would most likely have gone straight to Option A in Fig. 3a on the basis of spacing alone. While the spacing item might be improved by giving an image of the solid state as a reference point, it should be noted that particle diagrams of the liquid state appearing in other items all showed appropriately closely spaced particles.

One further particle item ('Atom13') was significantly underfitting for the whole sample but showed an acceptable fit when calibrated using the upper quartile of students. The plot of observed success suggests lucky guessing amongst lower ability students was distorting the picture. This was a difficult item involving diagrams showing atoms bonded in giant structures and a large amount of guessing is not surprising. For the rest of the particle items, most showed a good fit with a few on the edge of acceptability (see Johnson and Tymms 2011) for the interpretation of fit statistics).

The Variable Described by the Particle Model Items: A Learning Progression

Omitting the liquid spacing item, but including 'Atom13' with its difficulty calibrated on the top quartile, the items were placed in order of difficulty and examined in terms of their conceptual content. Items addressing the same aspects could be grouped together in relatively tightly defined regions on the scale and the positions of understandings addressed by single items make sense in relation to others. Figure 7 shows the outcome in terms of ideas. All boxes with a stated range of difficulty represent a group of more than one item. For boxes without a stated range, the vertical midpoint gives the difficulty value. In all but two cases where different items had the same difficulty, these correspond to single items. The scale in Fig. 7 is anchored at an arbitrary value of 50 for the mean item difficulty. (Ten units on the scale in Fig. 7 equals 1 unit on the ability minus difficulty scale of Fig. 2.) The key point is that the scale shows the order and the relative increments in difficulty from one idea to the next. The description of Fig. 7 that follows is an expanded version of a section in supplementary material accompanying the online version of Johnson and Tymms (2011).

Bottom left of Fig. 7, two items addressing the association of a substance with a type of particle in a representation (distinguished by shape and colour) enter at a difficulty of 32. Here the student is able to link the number of different particles to the number of substances. However, this association doesn't necessarily mean the particles are seen as being the substance. Three items exploring whether particles are seen as being the substance, for the solid, liquid and gas states, respectively, group together higher up at 39. However, at this level the particles are viewed as having different sizes (e.g. they would choose Option B in Fig. 3b). It seems likely that these 'particles' are viewed as being small pieces which have all the properties of the observed sample. Choosing particles having the same size is at 48 for a sample in the liquid state (Option D, Fig. 3b) and 55 for a sample in the solid state. More items using different substances are needed to confirm any real difference between the liquid and solid states, but it is possibly easier to think of a liquid sample 'breaking' into equal sized bits than a solid sample. (There was not an item looking for a corresponding distinction in the gas state.) Individual particles not having macroscopic character is more difficult, with the four items addressing this idea clustering between 60 and 63. Three items targeting the idea of nothing/empty space between particles fall between 65 and 69. The contexts of solid copper and gaseous methane are close together at 65 and 66 with liquid water at 69. Water may present a greater challenge than other examples of substances in the liquid state due to ideas of dissolved air ('air' was the most popular distracter in all three items).

The two modes of items on intrinsic motion (array and single particles) produced mixed results. With the solid state, the difficulties were similar (array-60, single-56) and show this to be the most challenging state. Differences between the two modes were more marked for the liquid and gas states. Array and single were at 32 and 47 respectively for liquid, and 28 and 37 for gas. Given the disparities, the positions of

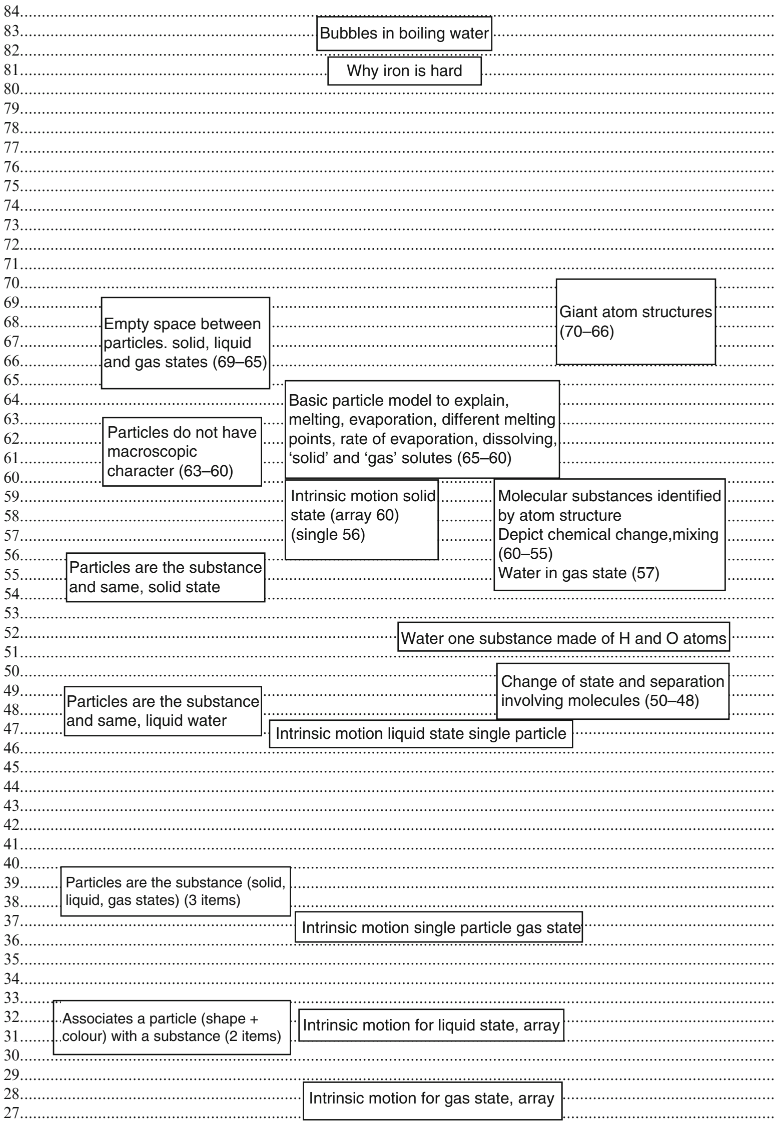


Fig. 7 A learning progression for the particle model (Adapted from Johnson and Tymms 2011, p. 869)

these ideas cannot be given with any precision and further investigation is required. However, it seems that intrinsic motion is easier for the gas state than the liquid state (Johnson and Tymms 2011, supplementary material, p. 4).

As noted, we cannot say where an understanding of particle spacing in the liquid state might be on the scale since the item's difficulty did not fit with the variable (for whatever reason).

Seven of the nine items on using the basic particle model to explain physical phenomena group together between 60 and 65. Of these melting stands apart at 65 with the rest between 60 and 63. The slightly higher value for melting may or may not be significant, but it seems possible that misconceptions about particle spacing in the liquid state were interfering. The options for the melting item were given earlier, and many pupils were attracted to 'moving apart' instead of 'start to move around but staying close together'. Of the remaining two items out of the nine, students' preoccupation with spacing was to the fore in one about why iron is hard, which was high up at 81. Most opted for 'the particles are close together' with few choosing 'the particles don't easily change neighbours'. The most difficult item, at 83 on the scale, concerned the representation of a bubble in boiling water. In addition to the idea of empty space between particles as opposed to air (already at 69 for water in the liquid state), knowledge of hydrogen and oxygen as gases seems to add to the difficulty. Only 7 % of 1,154 students answering chose an image of water particles spaced apart with nothing in between.

Making the distinction between atoms and substances is important. For example, an oxygen atom is not the same as the substance oxygen (O_2). The two-option item noted earlier where pupils chose between water being 'one substance made of hydrogen and oxygen atoms' or 'two substances, hydrogen and oxygen', registers at 52.

Items using molecular atom structures to represent various changes cover quite a large region on the scale. Between 48 and 50 are two items, one a change of state (not specified as melting or boiling) and one a separation. Higher up between 55 and 60 were four items, two on chemical change, one showing substances forming a mixture and one about water in the gas state. The latter item showed a video of a drop of liquid water being injected into a sealed hot gas syringe (150 °C) with the plunger moving out to give a clear, transparent interior. The three options showed: (A) separated water molecules; (B) separated hydrogen and oxygen atoms; (C) separated hydrogen and oxygen diatomic molecules. At 57 on the scale this item was much easier than the one on a bubble in boiling water (though the intervening space between the molecules/atoms was not directly addressed). Two items where the identity of a substance is embodied in the repeating unit of a giant structure of atoms fall at 66 and 70, respectively.

Where Are the Students on the Scale?

On the basis of the MidYIS scores, we know the Batch 1 year group samples are comparable. Using the Batch 1 data for the wider study on the concept of a substance (excluding underfitting items and the 6 % of underfitting students) gives mean substance abilities of 50.1, 52.5 and 54.9 for students at the end of Years 7, 8 and 9, respectively. The corresponding standard deviations are 7.4, 7.7 and 8.6 (Johnson and Tymms 2011). From the MidYIS data we also know our sample is above the national average by about one standard deviation. Therefore, adjusting the Year 9 mean by its standard deviation gives an estimated national mean of around 46.

Discussion

All but one of the particle items seem to belong to a variable which measures their relative difficulties. Furthermore, in terms of the conceptual content, a coherent picture has emerged. The sample size is substantial giving good reason to suppose the variable has widespread application. One limitation is the varying numbers of students per school and per year groups within schools which do not allow proper examination of differential item functioning by school. 'Although consistency across schools is the overriding position, there may be some differences arising from different curricular experiences (which would need to be known)' (Johnson and Tymms 2011, p. 872). It is perhaps surprising that different ages, schools and teachers did not produce a much greater variation in the responses. Even the patterns of choices amongst distracter options were very consistent. Another limitation is that some ideas are only addressed by one item and the variation with different contexts should be investigated. Intrinsic motion needs more attention and ideas of forces between particles could be explored in more detail.

Despite the limitations of the study, the data are good enough to suggest that Fig. 7 goes some way towards describing a typical pathway for the development of students' understanding of the particle model, i.e. a learning progression. The Rasch model defines student ability as the point where there is 50 % chance of success. For summative assessment purposes this might not be enough to claim a student understands this or that idea – a higher likelihood seems more appropriate. The key points about Fig. 7 are the sequence and the interval scale showing the increments in difficulty from one idea to the next. For more discussion on wider issues relating to leaning progressions the reader is referred to Johnson and Tymms (2011). The remaining discussion here will focus on particle ideas, first on the results and then on a comparison with the Author's previous longitudinal study.

The progression in Fig. 7 can be mapped to the Models A, B and C noted earlier. At 39 on the scale, the idea that particles are the substance, but of different sized pieces, corresponds to a primitive Model B. One suspects the sizes of these little pieces are envisaged to be not much smaller than that which could be directly observed. With abilities below 39, students are more likely to choose the options depicting versions of Model A. Of course, no other alternative models were offered, and we cannot be sure what they might be thinking other than matter is not particulate. From 48 to 55 represents a more developed Model B where the particles are all the same but are still viewed as having the macroscopic properties. Perhaps students are now zooming down to much smaller sizes in their imaginations, so beginning to free themselves from the immediacy of everyday experience. (Items addressing the sizes of particles would be useful but would also involve an understanding of numbers.) Losing the need to ascribe particles with macroscopic character corresponds to Model C and is a step further up the scale in the region of 60–63. Figure 7 also indicates starting to use particle ideas to explain phenomena coinciding with Model C. On the face of it, this makes sense – one needs a good understanding of the model before one can use it.

Interestingly, the items using molecular atom structure diagrams come before Model C, including those depicting chemical change. From a logical point of view, ideas of atoms are incompatible with Model B. If the 'basic' particles are like the observed substance, what are these atoms? However, in terms of learning, the incompatibility (cognitive conflict) might help students to relinquish macroscopic thoughts about the particles and so spur them on to Model C. Nevertheless, for ideas of atoms to have a chance one suspects students should at least be thinking in terms of particles being the substance (have reached an ability of around 55).

Particle spacing for the liquid state deemed midway between the solid and gas states is a very well-known misconception and one that some science text books are guilty of propagating (Harrison and Treagust 2002). However, perhaps less well appreciated is the significance of spacing in students' thinking – the ramifications go beyond producing acceptable particle diagrams. If states are simply identified by spacing, this is a 'short cut' which circumvents a deeper engagement with the model. The critical difference between the solid and liquid states is in the movement of particles, not the spacing. The solid state is hard because particles do not easily change neighbours – not because they are close together. The liquid state is runny because particles can move around, not because they are significantly further apart. Importantly, these explanations of hardness and runniness do not rely on the character of individual particles. It might be worth reminding students that the particles are further apart in ice than liquid water. If a state is identified by spacing alone, the characteristic properties are yet to be explained (save the greater volume of the gas state), so it would make sense to attribute these to the particles themselves. Misplaced emphasis on spacing could be blocking students' development.

For intrinsic motion, the relatively low difficulties of the gas items (array and single particle) and the liquid array item is perhaps a little surprising given the problems with intrinsic motion reported by other studies. For example, not one student in Westbrook and Marek's (1991) study (which included 100 undergraduates) invoked random intrinsic motion to explain the diffusion of a dye through water. Novick and Nussbaum (1981) report only half of their age 16+ sample using constant motion to explain why particles in the gas state are uniformly distributed. The use of animation with the items in this study may have reduced their difficulty. The motion is being presented as intrinsic and the cause of the motion was not explored. The students were also not being asked to explain a phenomenon, and we have already noted their difficulty with implicating motion for melting. The validity of using animated versus non-animated items to explore students' understanding of intrinsic motion is something to explore. The increase in difficulty from gas to liquid to solid within each of the two item modes in this study is entirely consistent with Talanquer's (2009) literature analysis given earlier. To see how much more difficult the animated solid state items were is noteworthy. It is also interesting to see intrinsic vibrational motion for the solid state coming just before Model C. It makes sense that a full appreciation of intrinsic motion contributes to relinquishing macroscopic thoughts about particles. However, as discussed in the introduction, Fig. 7 shows particle movement is quite compatible with Model A for the liquid and gas states. Attention to particle movement of itself is not necessarily going to develop students' understanding beyond Model A.

In terms of students' progress, the projected national mean of around 46 on Fig. 7 by the end of Year 9 needs to be treated with caution. Nevertheless, even allowing for a degree of underestimate, it suggests most are in the range of Model B, with less than 10 % reaching Model C. This is in keeping with the widespread difficulties reported in the literature.

Overall, the progression in Fig. 7 matches the findings of the Author's previous longitudinal study, but there are some differences. Most of the students categorised as Model B in the longitudinal study seemed to accept the idea of empty space between the particles, but in Fig. 7 this appears above Model C at 65–69. In the longitudinal study, particle ideas had been introduced in a substance-based framework: particles were identified as particles of specific substances. In contrast, it is very likely that most of the students in this study had been taught particle ideas through a 'solids, liquids and gases' framework (as advocated in the English National Curriculum) where the language talks of particles 'in solids' or 'solid particles' (ditto 'liquid' and 'gas'). Elsewhere, we have argued that the 'solids, liquids and gases' framework could be causing difficulties for students (Johnson and Papageorgiou 2010). A substance-based approach that focuses on why a substance can be in any of the three states (rather than solids, liquids and gases as separate types of matter) places emphasis on the particles being the substance which could make the idea of nothing easier to accept. If the particles are the substance, there is not anything else – i.e. there is nothing.

In the longitudinal study there were cases of students with Model B finding particle ideas helpful (e.g. mixing up explains dissolving even if one thinks the particles are still 'solid' and 'liquid'). Some of the items on explaining changes had been expected to locate below Model C on the variable. That none are below could reflect the different modes of assessment (interview vs. fixed-choice), or it could be that a substance-based approach allows students to start using particle ideas before attaining Model C. We must also remember that the Rasch model is based on probabilities (Fig. 2) and that some students at around 55 on the scale will be getting items in the region of 60–65 right. It is difficult to say what might be going on. A study directly comparing interview responses with fixed- response choices would be useful.

Any comparison with the students' progress in the longitudinal study must be treated with great caution, but it worth noting that just under 50 % of the interview sample was categorised as Model C in Year 9. The interviewees ($n=33$) were a stratified sample with two drawn from the top, middle and bottom of the achievement range, as judged by their teachers at the start of Year 7, in each of the six classes (three students dropped out during the study, one from each level). The top students could have been at the very top, but the middle students will have been somewhere around the middle and some of these must have been at Model C (if just under half of all were). Therefore, a conservative estimate would suggest the students in the longitudinal study made much better progress even compared to the above average sample of students in this study. There are many possible explanations, but this could be indicating a substance-based approach is more effective than the traditional 'solids, liquids and gases' approach. Almost certainly, the substance-based approach is not worse and merits serious consideration. Furthermore, with the benefit of insights gained from the longitudinal study, there are many places where the teaching scheme could have been better focused. Johnson and Roberts (2006) detail a substance-based approach to introducing particle ideas informed by the longitudinal study that may be of interest to readers.

Conclusion

Rasch modelling has been fruitful and this study provides sufficient evidence to warrant further investigation into a learning progression for students' understanding of the particle model. Figure 7 represents a first attempt to be refined. Importantly, the proposed progression generates specific questions to be explored (such as those raised in the discussion above) which will advance our understanding of students' learning. Having a suggested progression provides a framework for a systematic programme of research. Figure 7 is a creature of the prevailing 'solids, liquids and gases' approach and whether a substance-based approach would bring significant changes to the relative difficulty of ideas remains to be seen. The main line of progression from Model A to B to C is unlikely to change, but there are grounds for supposing the rate of students' progress would be much improved.

Acknowledgement The project was supported by an ESRC award (Grant reference: RES-000-22-1460).

References

Andersson, B. (1986). Students' explanations of some aspects of chemical reactions. *Science Education, 70*(5), 549–563.

Bond, T., & Fox, C. (2007). *Applying the Rasch model: Fundamental measurement in the human sciences* (2nd ed.). Hillsdale: Lawrence Erlbaum Associates.

Duncan, R., & Hmelo-Silver, C. (2009). Editorial: Learning progressions: Aligning curriculum, instruction and assessment. *Journal of Research in Science Teaching, 46*(6), 606–609.

Garnett, P., Garnett, P., & Hackling, M. (1995). Students' alternative conceptions in chemistry: A review and implications for teaching and learning. *Studies in Science Education, 25*, 69–95.

Harrison, A. G., & Treagust, D. F. (2002). The particulate nature of matter: Challenges in understanding the submicroscopic world. In J. K. Gilbert, O. De Jong, R. Justi, D. Treagust, & J. H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 189–212). Dordrecht: Kluwer Academic.

Johnson, P. M. (1998). Progression in children's understanding of a "basic" particle theory: A longitudinal study. *International Journal of Science Education, 20*(4), 393–412.

Johnson, P., & Gott, R. (1996). Constructivism and evidence from children's ideas. *Science Education, 80*, 561–577.

Johnson, P., & Papageorgiou, G. (2010). Rethinking the introduction of particle theory: A substance-based framework. *Journal of Research in Science Teaching, 47*(2), 130–150.

Johnson, P., & Roberts, S. (2006). *Stuff and substance (A multimedia CD ROM)*, Gatsby technical education products. www.sep.org.uk. Also freely available at http://www.nationalstemcentre.org.uk/elibrary/search?term=Stuff+and+Substance. Website accessed 6/1/2012.

Johnson, P., & Tymms, P. (2011). The emergence of a learning progression in middle school chemistry relating to the concept of a substance. *Journal of Research in Science Teaching, 48*(8), 849–984.

Krnel, D., Watson, R., & Glazar, S. (1998). Survey of research related to the development of the concept of 'matter'. *International Journal of Science Education, 20*(3), 257–289.

Linacre, J. (2005). Winsteps Rasch measurement, Version 3.59.1.

Liu, X. (2001). Synthesizing research on conceptions in science. *International Journal of Science Education, 23*(1), 55–81.

MidYIS. (2011). www.midyisproject.org. Website accessed 25 Mar 2011.

National Research Council. (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, DC: The National Academies Press.

National Research Council. (2001). *Knowing what students know: The science and design of educational assessment*. Washington, DC: The National Academies Press.

Novick, S., & Nussbaum, J. (1981). Pupils' understanding of the particulate nature of matter: A cross-age study. *Science Education, 65*, 187–196.

Sadler, P. M. (2000). The relevance of multiple choice tests in assessing science understanding. In J. Mintzes, J. Wandersee, & J. Novak (Eds.), *Assessing science understanding* (pp. 249–278). San Diego: Academic.

Smith, C., Anderson, C., Krajcik, J., & Coppola, B. (2004). *Implications of research on children's learning for assessment: Matter and atomic molecular theory*. Paper commissioned by the Committee on Test Design for K-12 Science Achievement, Center for Education, National Research Council.

Talanquer, V. (2009). On cognitive constraints and learning progressions: The case of "structure of matter". *International Journal of Science Education, 31*(15), 2123–2136.

Westbrook, S. L., & Marek, E. D. (1991). A cross-age study of student understanding of the concept of diffusion. *Journal of Research in Science Teaching, 28*, 649–660.

Wiser, M., & Smith, C. (2008). Learning and teaching about matter in grades K-8: When should atomic-molecular theory be introduced? In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 205–239). New York: Routledge.

Wright, B. D., & Stone, M. H. (1979). *Best test design*. Chicago: MESA Press.

Implicit Assumptions and Progress Variables in a Learning Progression About Structure and Motion of Matter

Hannah Sevian and Marilyne Stains

Introduction

Understanding of the structure and properties of matter is a foundational pursuit of science. Likewise, developing students' facility in explaining and predicting natural phenomena with known scientific models is of central importance in the teaching and learning of science. Applying models of the structure of matter at the particulate level to explaining and predicting properties of the macroscopic world is an historical approach to teaching about the nature of science and to comprehending nature itself (Scheffel et al. 2009). However, students at all ages demonstrate difficulty in understanding fundamental ideas about the structure of matter and relationships to properties of materials (e.g., de Vos and Verdonk 1996). This persistent problem, evident across ages ranging from early childhood to undergraduate learning, has prompted researchers to investigate the development of understanding about concepts of matter over long periods of time, and whether there are deep reasons that might account for the difficulties (Kind 2004; Nakhleh 1992; Taber and García Franco 2010; Talanquer 2009).

This chapter presents one approach to investigating this problem, through the characterization of how students across a wide age range of backgrounds understand the structure and motion of matter at the particulate level. We begin by reviewing relevant aspects of a hypothetical learning progression (hereafter LP) on the particle nature of matter that was presented by Talanquer (2009). This LP organizes the evolution of learners' thinking in terms of specific implicit assumptions (hereafter IAs)

H. Sevian (✉)
Department of Chemistry, University of Massachusetts Boston, Boston, MA, USA

Division of Undergraduate Education and Division of Research on Learning, National Science Foundation, Arlington, VA, USA
e-mail: hannah.sevian@umb.edu

M. Stains
Department of Chemistry, University of Nebraska-Lincoln, Lincoln, NE, USA

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_4,

that they are relying upon. IAs are presuppositions about the nature of entities that guide and constrain people's reasoning involving those entities. We focus on two of the dimensions of IA evolution hypothesized by Talanquer: structure and dynamics at the particle level. We explain the ways in which our study is situated in the general ways in which LP research varies and show that the approach of organizing the evolution of learners' thinking in terms of IAs is able to bring coherence to a number of studies about the capacities of students to understand the particle nature of matter, as well as the difficulties students exhibit. Initially assuming Talanquer's dimensions as progress variables along which the evolution of students' thinking from less to more sophisticated could be characterized, we developed an instrument to ascertain which IAs constrain a student's thinking about a particular phenomenon that relies on reasoning about the structure and motion of matter at the particle level. The instrument relies on an assumption that people generate instantaneous mental models when presented with a novel question, and these mental models are constrained by the IAs held by the person. Examples of students' responses from application of the instrument, whose validation was reported elsewhere (Stains et al. 2011), are used to show how IAs constraining students' thinking are able to be identified using the instrument. Application of this instrument to a large sample of students across a wide range of ages captured distributions of students' thinking patterns at each grade level. We discuss how this process of validating the LP enabled us to refine what the progress variables are in the LP. The iteration from hypothetical LP to assessment to interpretation of student data from the assessment enabled not only a refinement of the LP but also a deeper understanding of how a specific curriculum influences the progress of learning by the presence or absence of deliberate practice in using particular IAs. We discuss the differences in distributions of thinking patterns that were observed across grade levels, relationships to the curriculum followed in the schools from which participants were drawn, and ways in which the LP could provide guidance in the use of curriculum to improve student outcomes.

Learning Progressions

LPs describe learning over extended periods of time, usually more than 1 year. According to a recent review (Salinas 2009), they generally describe how student learning becomes more sophisticated in some aspect of a discipline. They are usually situated within a theory of cognition, take into account curricular and instructional conditions, and they can include considerations of social and cultural contexts. LPs are increasingly of interest in institutional and policy contexts, most recently particularly in the USA in influencing the development of national frameworks for mathematics and science education from preschool through graduation from high school (National Research Council [NRC] 2007; National Council of Teachers of Mathematics 2010; President's Council of Advisors on Science and Technology 2010). The term "learning progressions," as used in this chapter, includes a variety of work occurring under many names. LP has tended to be the term of choice in science education in the USA, while mathematics education in the USA has favored the term learning trajectories. In Europe, similar work has evolved under the names teaching experiments, and teaching-learning sequences.

The promise of LPs lies in their ability to guide the coordination of curriculum, instruction, and assessment in order to provide sustained opportunities over many years for students to engage with core ideas and develop connections between them. In recent years, the National Academy of Sciences in the USA has convened a series of consensus studies focusing on the state of research on learning and how it can guide further research, as well as practice and policy. LPs were defined as "descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time (e.g., 6–8 years)" (NRC 2007, p. 219). The role and conditions for the success of LPs have been articulated as "They are crucially dependent on instructional practices if they are to occur… traditional instruction does not enable most children to attain a good understanding of scientific frameworks or practices, but there is evidence that the proposed learning sequences could occur with appropriate instructional practices." The *Framework for K-12 Science Education*, which is now providing the framing for the current revision of the national standards for science education in the USA, provides the following guiding assumption: it "emphasizes developing students' proficiency in science in a coherent way across grades K-12 following the logic of learning progressions" (NRC 2012, p. 33).

Approaches to Studying LPs

While there is general consensus that LPs offer promise in guiding education, the field has not yet come to consensus on more detailed aspects of what LPs are, particularly in terms of how they are developed, represented, and studied. A recent paper by Duschl, Maeng, and Sezen (2011) provides an analytical review of a wide variety of LP research in science education in the USA and Europe over several decades, with connections to learning trajectories in mathematics. Their review focused on how LPs are created, and how they are validated and described. They characterize four variations in approaches to studying LPs: (1) the subject matter of the LP, (2) how the boundaries of the LP are defined, (3) how intermediate levels are studied, and (4) the explicit or implicit model of conceptual change associated with the LP.

1. The Subject Matter of the Learning Progression. Most LPs tend to focus either on scientific knowledge without integrating science practices or on science practices without integrating domain knowledge.
2. Boundaries of the Learning Progression. How the boundaries of an LP (i.e., lower and upper anchors) are defined tends to vary. Some LPs provide explicit definitions of lower anchors, while others describe them more implicitly, for example, intuitive accounts by students of familiar macroscopic events. Upper anchors tend to be more clearly defined and usually correspond to statements of scientific knowledge and/or practices that students are expected to master.

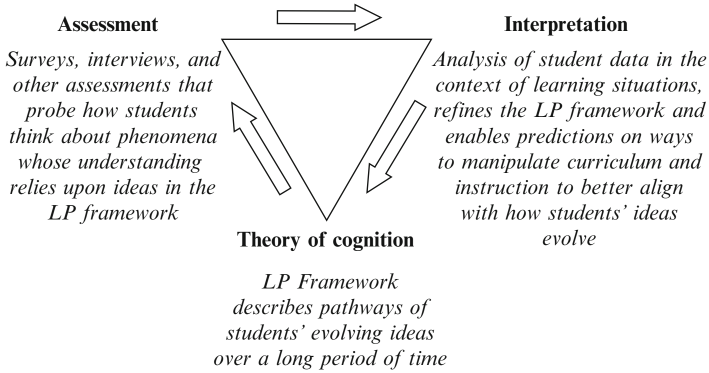


Fig. 1 Validation cycle in the development of an LP

3. Study of Intermediate Levels. There is variation in how intermediate levels of understanding are studied, described, and related to instruction. Regarding the proximity to instruction, some LPs describe linear sequences of steps not necessarily connected to instruction (e.g., Alonzo and Steedle 2009).
4. The Model of Conceptual Change Associated with the Learning Progression. There are two classes of conceptual change models at the foundation of LP research, which Duschl et al. identify as a misconceptions-based "fix it" view and a "work with it" view. They associate these two classes of conceptual change models, respectively, with two types of LP: (i) validation LPs, which seek to validate initial sequences and levels of progression, and (ii) evolutionary LPs, which define and refine developmental pathways by identifying productive ways of reasoning that can be used by learners to make meaning. They find that many LPs primarily target canonical understanding of a topic, and only infrequently do they focus on how learners use knowledge. They argue the same point made in *Taking Science to School*, that focusing on a "fix it" view of misconceptions in teaching for conceptual change can work against addressing conceptual change.

Common to most approaches in developing LPs is an iterative process that begins with a hypothetical LP and involves empirical validation by collecting data on student learning whose interpretation then feeds back into revising the LP and providing predictions on how learning can be optimized by modifying curriculum and instruction to better account for the actual progression of students' learning. This validation process, which can be represented as an adaptation of Mislevy's Conceptual Assessment Framework (NRC 2001; Mislevy et al. 2002), is illustrated in Fig. 1. Each iteration or cycle results in an improved LP framework with better understanding of how curriculum and instruction influence students' progression through the LP as well as the reverse.

Such a validation cycle tends to fit well within a design-based research framework (Cobb et al. 2003; Collins et al. 2004), which has seen increasing usage over the past 5 years in the USA. Considerable discussion in the field has centered on framing exactly what taking a design-based approach means (e.g., Design-Based Research

Collective 2003; Kelly 2004), and it is beyond the scope of this chapter to summarize the larger discussion. Our own approach in our larger research project involves studying the context (e.g., the teaching and learning actually occurring in schools), deriving goals for the research that include respecting and improving teaching and learning within the context, having research questions that emerge from the goals, iterating through phases that refine the design and theory, and converging iteratively on knowledge in which the stakeholders have input and derive value. A small part of this approach is reported in this chapter, with one iteration of validation of one part of a larger LP about chemistry that is under study.

Our Theoretical Commitments in Studying an LP on Chemistry

In relation to the four variations discerned by Duschl et al. (2011), we have made the following specific commitments in studying LPs:

1. *Subject matter of our LP*: Our full LP is concerned with how student thinking about chemistry develops with training in chemistry. The part of this LP research reported in this chapter focuses on scientific knowledge around the particle nature of matter, and particularly relationships between structure of matter at the particle level and properties of materials. To assess student thinking about these structure-properties relationships, we probe student thinking about three initial conditions imposed on a phenomenon whose explanation relies on this thinking – diffusion in a gaseous mixture. While other phenomena relying upon the same thread of thinking could have been chosen instead (e.g., solutes dissolving in water, phase changes), we wanted to probe a phenomenon that was not taught in the curriculum in the schools from which the study population was drawn, so that we could more accurately measure how students' IAs shaped their thinking. In particular, we wanted to more cleanly discern this from what students may remember of what the teacher taught. We are concerned with the ideas that students have and the underlying IAs that constrain those ideas. In keeping with the observation of Duschl et al., our LP focuses primarily on scientific knowledge rather than scientific practices; that is, while the use of particle-level models of matter is important to structure-properties relationships, the practice of modeling is not the focus of our assessment.
2. *Boundaries of our LP*: The part of the full chemistry LP that is the focus of this chapter describes changes in IAs (explained below in the section where the initial LP of the structure of matter is described) that guide and constrain learners' reasoning about key elements in the LP. Our intent is to identify cognitive resources that can support productive thinking as learners' understanding is deepened when they grow to own more sophisticated assumptions upon which they can rely in conditioned ways. There is not a specific age assumed for the lower anchor of the LP. The IAs we probe assume learners are familiar with the ideas that there are different kinds of materials and that different materials have unique properties. The upper anchor is defined by the most scientifically accurate IAs in the LP.

3. *Intermediate levels*: We take the view, described by Wiser and Smith (2008), that some intermediate levels can be described as "stepping stones" in students' learning that can be productive ways of thinking and may be reconceptualized as learners' understanding deepens through instruction, while other intermediate levels may not be productive. We consider learners' ideas to be constrained but dynamically interacting with an environment that includes instruction (Brown and Hammer 2008). Our approach to studying the LP is concerned with identifying and characterizing the evolution of metastable intermediate levels (some of which are productive stepping stones) toward greater scientific sophistication. We are ultimately concerned both with the internal constraints (IAs) and external conditions (e.g., instruction) in support of this evolution. The role of curriculum, instruction, and assessment are therefore important in understanding this evolution and form part of our larger study. The focus of this chapter is to report on one cycle of validation of part of the structure-properties relationships piece of the chemistry LP, to show how the progress variables and IAs by which they are measured are clarified by this process. While instruction certainly contributes to the evolution, we limit the scope of this chapter to describing the refinement of the LP through measuring learners' IAs, and we do not report on future cycles that would involve interactions between instruction and the evolution of learners' ideas through intermediate levels when curriculum and instruction are adapted to better align with the LP.
4. *Model of conceptual change*: Our approach to studying the LP would be considered by Duschl et al. to be an evolutionary LP. We are concerned with describing learning in terms of changes in, or acquisition of new, IAs by learners. Ultimately, we seek to identify productive intermediate understandings – stepping stones, as explained in the previous item – through which learning optimally progresses and which have explanatory and predictive power. We believe these stepping stones offer guidance for how to arrange curriculum and instruction to support ideal growth in learners' sophistication of ideas as they build toward more scientifically accurate understanding.

Method

Part 1: Theory of Cognition

The Structure of Our LP Framework: Progress Variables and Intermediate Levels

In order for an LP to be useful in measuring progress of learning, there must be a way in which the current state of understanding of a learner can be characterized and the student's progress of learning can be measured. One way to consider the representation of an LP is as encompassing three categories in a general framework: (1) progress variables, (2) identifiable/stable intermediate levels of understanding, and (3) individual assessments and their scoring rubrics (Sevian and Anderson 2012). The individual assessments are designed to relate student performance on items to the general framework.

Wilson (2009) describes progress variables as elements or dimensions of student performance that make possible a detailed comparison among levels or models. For example, Anderson and co-workers (e.g., Mohan et al. 2009) have studied for many years an LP describing how students reason about various processes that occur in carbon cycling (photosynthesis, cellular respiration, combustion, etc.) and the ways in which students practice reasoning about the processes. Mohan et al. characterized student reasoning in terms of the types of accounts given for the processes (e.g., force-dynamic narrative, scientific model-based). In continuing work (e.g., Jin and Anderson 2012), Anderson and co-workers have also explored other ways of characterizing student reasoning about processes (e.g., thinking at different scales, association, and tracing of matter and energy). The LP study that we present in this chapter describes how students reason about one phenomenon, diffusion, which occurs in chemical systems, and the ways in which students practice reasoning about this phenomenon using what they understand of structure-properties relationships. We characterize students' reasoning in terms of IAs. Our initial progress variables, along which the IAs that constrain students' reasoning can be characterized, were initially taken to be the dimensions in the initial hypothetical LP, described below.

Intermediate levels of understanding are descriptions of consistent ways in which learners think. They present a particular view of how the world is, and they rely on identifiable and distinct locations along each progress variable. For example, in their LP describing levels of understanding of upper elementary through high school students about carbon cycling in socio-ecological systems, Mohan et al. (2009) describe four patterns, or levels of understanding, in the ways that students reason in terms of progress toward more sophisticated reasoning. Similarly, in a related paper within our larger research study (Stains and Sevian 2013), we describe five distinct intermediate levels, each consisting of specific combinations of IAs within different progress variables of the structure and motion of matter, into which the majority of student reasoning about diffusion processes falls.

While a scoring rubric can be applied to individual assessments to determine indicators of students' understanding and ability to reason that are generally characterized as less or more sophisticated, these assessments are designed to relate student performance on items to the general framework described above, of progress variables and intermediate levels. Neither the four observed intermediate levels of Mohan et al. nor our five intermediate levels which we present elsewhere are a prescriptive pathway of progress. Rather, they describe typical places along which students' reasoning tends to rest for some time, and they are stable enough that their existence can be probed by assessments. There exists, however, the potential to misuse these intermediate levels as a prescriptive pathway, and several researchers have elucidated related concerns. For example, Wiser et al. (2012) make a convincing case that only some intermediate levels are productive stepping stones through which curriculum should be deliberately routed in order to optimize learning, while other intermediate levels could be detrimental to learning.

The Initial Learning Progression Relating Particle-Level Structure and Properties of Materials

The validation cycle begins with an LP framework as the theory of cognition, which we took to be the hypothetical LP presented by Talanquer (2009). In this section, we describe this initial LP, which describes the development of learning in terms of IAs. Talanquer (2009) argues that IAs can be used to make sense of and bring coherence to what is known already from many studies of students' reasoning. He describes IAs as common presuppositions that people hold about entities that exist and phenomena that occur.

In developing this hypothetical LP, many studies of how students understand the nature of matter were taken into consideration, as well as other research that focused on longitudinal and cross-sectional studies on how students develop an understanding of matter. The LP assumes that student reasoning in a realm is guided and constrained by IAs about the nature of entities and processes in that realm (Talanquer 2006, 2009). The organization of the LP is by IAs that constrain reasoning about matter, which were identified through his analysis of the studies. He summarized these findings into a hypothetical LP describing the evolution of these cognitive constraints along four dimensions related to the understanding of matter: (1) the structure of matter, toward the idea that matter is particulate; (2) the properties of matter, toward the idea that properties of a substance emerge from interactions between particles; (3) dynamics, toward the idea that the motion of particles is an intrinsic property; and (4) interactions, toward the idea that particles interact through intrinsic forces.

Two of these dimensions bear further explanation, as they are built upon in this chapter. In Talanquer's hypothesized LP, once learners ascribe to a view that matter is at least granular (rather than continuous), the *structure of matter* dimension is characterized by the likely evolution of IAs from a more novice *embedding* assumption, in which the structure of matter is described as a continuous medium that holds granules of substances, toward a more expert and scientifically sound *vacuum* assumption, which holds that empty space exists between particles. The vacuum assumption is generally accompanied by an assumption of matter as corpuscular, that is, made of distinctive types of particles. The *dynamics* dimension is characterized by an evolution of IAs starting from a novice assumption that particles are *static* or fixed in space. This evolves to a *causal-dynamic* assumption, in which the movement of particles occurs as a result of an external force, without which movement would cease, and later to a *contingent-dynamic* assumption, in which the movement still must be sustained, but the source of the force is internal. The more expert and scientifically sound assumption is *intrinsic-dynamic*, in which movement is recognized as an intrinsic property of particles.

Many pervasive ways of thinking (sometimes called misconceptions) can be explained as applications of IAs to explaining and predicting phenomena. For example, in a sequence of studies (Johnson 1998, 2005), an LP was determined through a 3-year, longitudinal, interview-based study, describing the progression of student understanding from a view that matter is continuous to three possible, more sophisticated end points: the particles are in the continuous substance, the particles are the substance but they have macroscopic character, or the particles are the substance and they do not have macroscopic character. A subsequent large-scale, cross-sectional assessment of views of the particle nature of matter held by middle school aged students found consistency with this LP (Johnson and Tymms 2011). The findings can be interpreted as consistent with the evolution of students' IAs from a view that matter's structure is continuous to embedded and (along the properties dimension of Talanquer's not explored in our study) from inheritance and substantialism toward elementalism and emergence. In similar ways, IAs can cohere many findings from the literature.

The perspective of IAs as constraining thinking, and resulting in well-known misconceptions, may also be consistent with the reasoning by young children about matter. Wiser and Smith have studied how younger students (preschool ages through middle grades) develop understanding of the atomic-molecular theory. They have studied the variety of ways in which students develop understanding over time, to define aspects of an LP that they have presented in various focuses in several papers (e.g., Wiser and Smith 2008). They find that there is a great deal of variety in how students conceptualize and reason about matter, weight, density, volume, and materials. Additionally, they find that the misconceptions displayed by students can be explained by a diversity of reasons, including the ways in which they conceive of the macroscopic world (concepts), how they come to know that world (epistemology), and the interactions of their beliefs, concepts, and epistemology. They argue that the structure of conceptual understanding is complex, such that "different aspects can be foregrounded in different contexts" (Wiser and Smith 2008, p. 207). For example, a conceptual change is observed in the phenomenon of children's thinking when "felt weight becomes peripheral *because* students have come to appreciate that objective measures are more precise and reliable, and they support lawful generalizations (e.g., about the relation of weight and volume)" (p. 207). In our view, the phenomenon of foregrounding some aspects depending on the context may be consistent with conditionalizing certain IAs in response to perceived cues.

Initial Hypothesis for the Model of Cognition

We set out to validate the initial LP by designing an assessment and then interpreting the results from the assessment in the context of the curriculum used in the schools from which the population drew. The initial hypothesis of the LP was taken to have two progress variables along which increasingly sophisticated IAs could be observed: (1) particulate level structure of matter and (2) dynamics of particles. The comparison between the initially hypothesized LP and the refined LP after one iteration of the validation cycle (see Fig. 1) is shown later in Table 3 (see section "Part 3: Interpretation").

Part 2: Assessment

Students incorporate intuitive knowledge and commonsense reasoning to form mental representations and then use these representations to make sense of the world. The role of intuitive knowledge and commonsense reasoning in students' conceptual understanding has been extensively reported in cognitive science and science education literature (Chi 2005; diSessa 1993; Talanquer 2006; Vosniadou 1994). We now turn to describing how we captured representations of students' conceptual understanding and analyzed them in terms of the IAs constraining them.

Measuring Implicit Assumptions

We reasoned that it would be possible to test the validity of the LP by developing assessments that pose questions causing students to generate representations about a concept. Such questions are called "generative questions" (Vosniadou and Brewer 1992). We hypothesized that if the students' representations rely on their IAs then we should be able to uncover the variety of IAs held by learners of various ages and in different contexts. There are many studies that focus on mental models as representations that are constrained by how students think. For example, Vosniadou and Brewer (1992) found in their study on the characterization of children's mental models of the Earth that children held rectangular and disc models of the Earth. These mental models were constrained by the children's assumption that the ground is flat. Thus, we followed the approach of designing an assessment instrument that poses generative questions that would cause students to create mental models constrained by their IAs. We note that where *mental models* are private and personal cognitive representations, *expressed models* are models derived from the mental models placed in the public domain through the use of different modes of representation, such as conversation, drawing, and writing. Technically speaking, it is not possible to directly measure mental models. Rather, mental models have usually been characterized through the analysis of expressed models. However, for simplicity in the ensuing discussion, both will be referred to as mental models.

Studies of mental models are most often done through interviews of relatively small numbers of people. As our interest was in determining how various combinations of IAs constrain students' thinking along progress variables, we were interested in collecting data from large numbers of students in order to have sufficient data to examine combinations of IAs that manifest in particular mental models. A survey for capturing students' mental models about the *Structure And Motion of Matter* (the SAMM survey[1]) was developed and validated, along with a scoring

[1]© 2010, Stains & Sevian, freely available at http://sites.google.com/site/sammsurvey/

scheme whose reliability was demonstrated (Stains et al. 2011). The survey design follows the generative question assessment strategy used by Vosniadou in interviews (e.g., Vosniadou and Brewer 1992). It presents a set of scenarios about a natural phenomenon, in this case diffusion of a scented gas in a room, in a unique way that students participating in this study likely had not previously encountered in instruction. It is important to reiterate that this particular phenomenon was selected over other possibilities (e.g., phase changes, dissolving process) because it is not explicitly covered in any of the curriculum materials used in the schools of participants in the study. The student is asked to represent the instantaneous mental model through writing and drawing. This mental model is not considered to be a complete, in-depth representation of a student's conceptual understanding of the topic. Rather, it is the understanding at the front of the student's mind, and as such, it is a representation of the assumptions held by the student that guide thinking at the moment of the assessment.

The three scenarios and associated questions are as follows:

– Question 1 presents a scenario of a glass of perfume broken on one side of a room and the student on the other side of the room. The student is asked to explain in a drawing and in writing how molecules of perfume move from the spill to the nose. The student is also asked to draw and explain the movement of one perfume molecule and why the molecule has that movement.
– Question 2 presents a scenario of two identical balloons containing identical amounts of scented gas in different rooms, with the only difference between the rooms being that one room is hotter than the other. The student is asked to state and then explain why, in drawing and in writing, in which room the smell would be sensed as stronger and in which room the smell would be detected sooner.
– Question 3 presents a scenario of two identical balloons in the same room, with different scented gases in them. The ball-and-stick structures and molecular formulas of the gases are provided. The student is asked to state and then explain why, in drawing and in writing, if both balloons were popped at the same time, which gas's smell would be observed first and which gas's smell would be stronger.

In all three questions, students are asked explicitly to describe and to represent the air in the rooms as well. The main points of the three scenarios are summarized in Table 1. Table 2 summarizes the multiple questions and modes through which the survey requests that students express their mental models.

Data from the SAMM survey were collected from 485 students from grade 8 (age 13) to upper-level undergraduate (fourth year of university) in a large urban school district, a community college, and a university, with all three institutions having wide diversity of race/ethnicity, socioeconomic status, and career aspirations. The surveys were scored using the scoring scheme (Stains et al. 2011), which revealed the specific IAs students exhibited. More details on the participants are provided in Stains et al. (2011). A full description of the development of the survey, including studies of its validity and the reliability of the scoring scheme, is also reported there.

Table 1 Three scenarios of the phenomenon of diffusion of a gaseous solute in a gaseous solvent that form the main three questions in the SAMM survey

Question	Scenario
1	Imagine that someone breaks a glass of perfume on one side of a room and that you are standing on the other side of the room. You begin to smell it after a short while because the perfume molecules get from the spill to your nose
2	Imagine that we have two identical balloons containing an identical amount of a scented gas. One balloon is placed in Room 1 and the other in Room 2. The two rooms are identical except that Room 2 is hotter than Room 1. You are standing in each room at the same distance away from the balloon
3	Imagine that we have two identical balloons containing the same amounts of two different scented gases, Gas A and Gas B. One balloon is filled with Gas A and the other balloon is filled with Gas B. The balloons are placed in a room at the same distance away from your nose. The balloons are popped at the same time

Table 2 Correspondence between question parts and progress variables that were ultimately measured

Clarified dimension assessed	Question 1: diffusion of perfume in air	Question 2: diffusion in hot vs. cold room	Question 3: diffusion of different molecules
Structure of air (solvent)	1d: drawn 1e: written	2c: drawn and written	3c: drawn and written
Origin of motion of solute particles	1c: written	2c: drawn and written	3c: drawn and written
Trajectories of solute particles	1a: drawn 1b: written 1e: written	2a: written 2b: written 2c: drawn and written	3a: written 3b: written 3c: drawn and written

Discussion of how the two dimensions of the initial LP were clarified as measurable by three progress variables through the validation process is reported in Part 3 of this chapter. Each question (numbered) has several parts (letters) which ask students to represent their thinking either in writing or by drawing a picture. For example, 1d refers to question 1, part d. The full survey may be accessed online (see footnote earlier for URL)

Part 3: Interpretation

Through the development of the survey and subsequent implementation with a large sample of students, we found that four distinct dimensions could be independently assessed: structure of perfume, structure of air, origin of motion of perfume particles, trajectories of perfume particles (Stains et al. 2011). Each of these is assessed in multiple question sub-parts and through both writing and drawing (see Table 2); however, one of these dimensions was dropped because the analysis of most students' surveys indicated thinking of the perfume as particulate. It is possible that this occurred because the questions asked students to show the movement of a single perfume molecule, thus restricting the way in which students expressed their ideas of the perfume structure.

In this section, we present the analysis of students' responses and the refinement to our understanding the progress variables of the LP that it enabled.

Refinement of the Learning Progression

Table 3 presents a comparison between the IAs identified in the *structure* and *dynamics* dimensions of Talanquer's LP, and the applications of those IAs to the phenomenon of diffusion in a gaseous mixture that the SAMM survey and associated scoring scheme are able to distinguish reliably between. The interpretation of student data enabled us to identify a *structure of gas* progress variable, which is closely related to Talanquer's *structure* dimension, and an *origin of motion* progress variable, which is closely related to Talanquer's *dynamics* dimension. It also enabled us to identify a *trajectories of particles* progress variable which is not directly mapped to any one of Talanquer's dimensions but rather appears as a combination of both structure and dynamics dimensions along which IAs evolve. The distinguishing of *origin of motion* and *trajectories of particles* as separate progress variables is described below, to illustrate the process of refining the LP. Some examples of students' drawings, also illustrating different items in the instrument, are shown afterward, in Figs. 2, 3, and 4, with the applications of the IAs to *structure of gas* [*solvent*], [*solute*'*s*] *origin of motion* and *trajectories of* [*solute*] *particles* identified.

First, we compare the *dynamics* dimension with our *origin of motion* progress variable. Within the *dynamics* dimension, Talanquer hypothesized four distinguishable IAs described earlier: static, causal-dynamic, contingent-dynamic, and intrinsic-dynamic. We observed five distinguishable categories of the application of these IAs to the phenomenon of diffusion in a gaseous mixture:

1. *The motion of solute molecules is caused by external forces*. Students exhibiting this thinking pattern consider the solute molecule's motion as being caused by external forces or agents outside of the solute molecule. These included air current or wind (e.g., some students drew fans or windows); inhaling or breathing, where the action of the nose attracts the molecules; an external force called "diffusion" that pushes molecules from one area of the room to another; a difference in concentration with an anthropomorphic attribution of molecules "needing" to go from higher to lower concentration; freedom to move due to lack of containment, but with the agent of movement being an external force; and heat causing movement by putting pressure on the molecules. Without the external agent, the molecules would not move. This view is most similar to the *causal-dynamic* IA, with aspects of the *static* IA.
2. *The movement of solute molecules is caused by external forces*, *but the motion is conditioned by certain features of the solute molecule*. Students holding this view state explicitly that external forces cause the solute molecules to move, but they demonstrate implicit recognition that the molecules move by themselves. For example, they indicate that at higher temperature molecules have faster speeds, or

Table 3 Comparison of the IAs of Talanquer (2009) and Stains et al. (2011) descriptions of successively more expert application of the IAs to the phenomenon of diffusion in a gaseous mixture

	Structure (Talanquer)	Structure of gas (Stains et al.)	Dynamics (Talanquer)	Origin of motion of particles (Stains et al.)	Trajectories of particles (Stains et al.)
Expert	*Vacuum* *Corpuscularity*	Microscopic	*Intrinsic-dynamic*	Molecules are always in motion	Perfume particle trajectories based on random collisions with microscopic particles; air influences trajectories
		Macro/ microscopic		Molecules' motion is conditioned by certain properties or features of the substance; molecules are always in motion	Perfume particles collide with other molecules but air molecules provide force/energy for them to move Perfume particle trajectories are random; air influences trajectories
			Contingent-dynamic		
	Granularity *Embedding*	Macroscopic		Molecules' motion is conditioned by certain properties or features of the substance; but molecules are not always in motion	Perfume particles collide with other molecules but air controls their trajectories Perfume particles radiate outward from spill; air influences trajectories
			Causal-dynamic	Molecules' motion is conditioned by certain properties or features of the substance, but external forces are the main agent of movement	Perfume particles collide or avoid other particles/walls; air influences trajectories Perfume particles move but not clear how; air influences trajectories
		Ignored/ absent		Motion of molecules is caused by external forces	Perfume particles move; air controls trajectories Perfume particles do not move by themselves; air controls trajectories
Novice	*Continuity*	Not coherent	*Static*	Not coherent	Not coherent

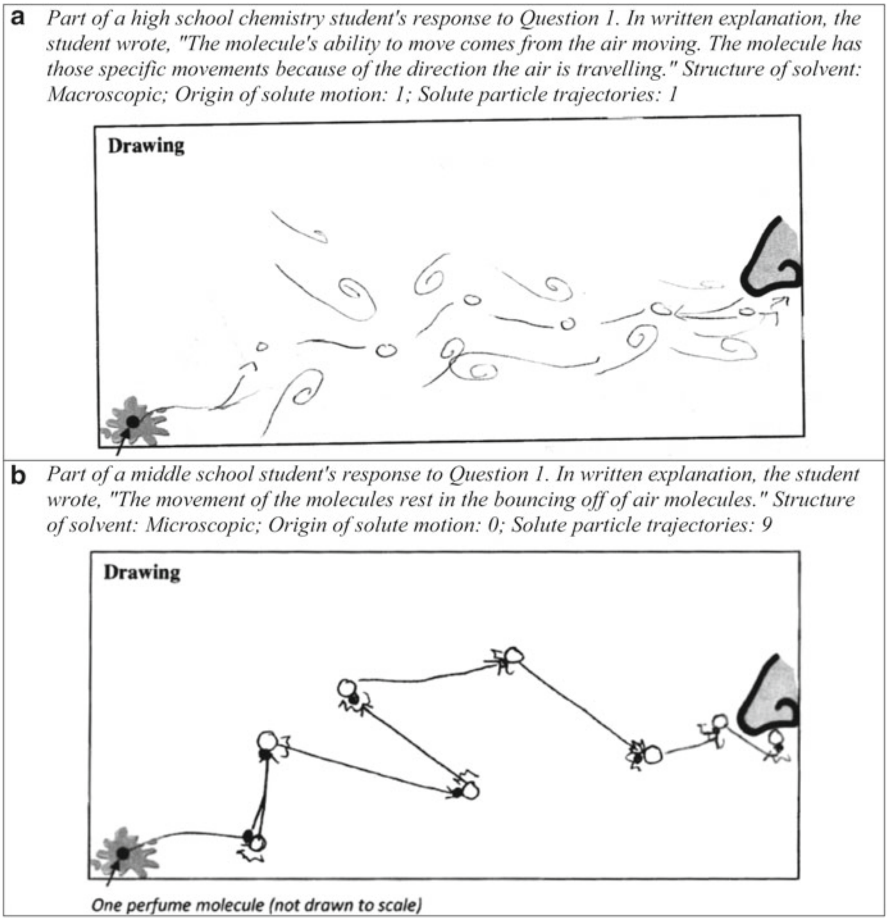


Fig. 2 Examples of student responses to Question 1 in the SAMM survey (see Table 1 for scenario). Students are asked to draw a picture to explain the movement of one perfume molecule going from the spill to the nose. *Scores* (refer to Table 3 and text describing it) indicate the thinking patterns exhibited in the student's entire response to the survey (based on consistency across all items, see Table 2) for the structure of solvent, origin of solute motion, and solute particle trajectories progress variables. The *numbers* shown with each example refer to the categories of thinking patterns described in the text for the last two of these progress variables

that molecules with lower mass move faster, or that certain atoms in the molecules allow them to move. They do not, however, recognize that molecules are in constant motion. This view has aspects of the *causal-dynamic* and *contingent-dynamic* IAs.

3. *Solute molecules move by themselves, but their motion is conditioned by certain features of the molecule*. Students with this thinking pattern explicitly recognize that the solute particles move by themselves as a result of some features of the molecules themselves, such as their size, number of electrons, or mass, or due to

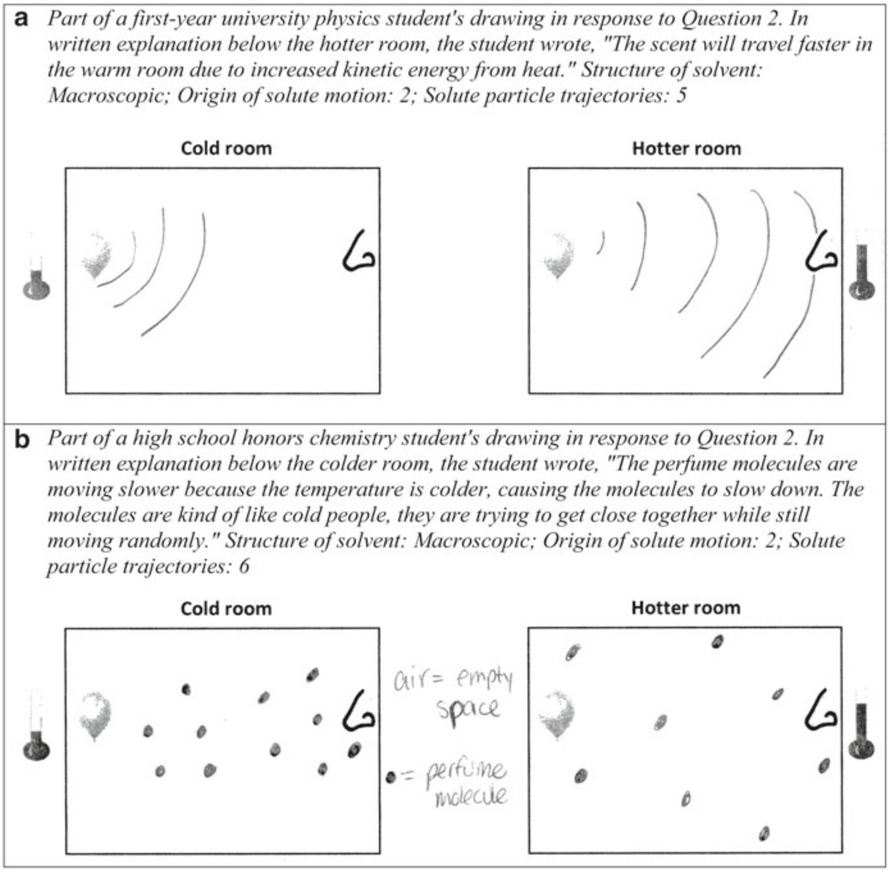


Fig. 3 Examples of student responses to Question 2 in the SAMM survey (see Table 1 for scenario). Students are asked to draw the perfume molecules and their movements, in the cold room and in the hotter room, soon after the balloons with their gases are popped. *Scores* (refer to Table 3 and the text describing it) indicate the thinking patterns exhibited in the student's entire response to the survey (based on consistency across all items, see Table 2) for the structure of solvent, origin of solute motion, and solute particle trajectories progress variables. The *numbers* shown with each example refer to the categories of thinking patterns described in the text for the last two of these progress variables

the state (i.e., gaseous) that they are in. Students do not, however, recognize that molecules are in constant motion. This view is most similar to the *contingent-dynamic* IA.

4. *Solute molecules are in constant motion*, *but their motion is conditioned by certain features of the molecule*. Students holding this view clearly and explicitly express that molecules are in constant motion and move by themselves. They attribute the motion to features of the molecules, such as size, number of electrons, or mass. This view has aspects of the *contingent-dynamic* and *intrinsic-dynamic* IAs.

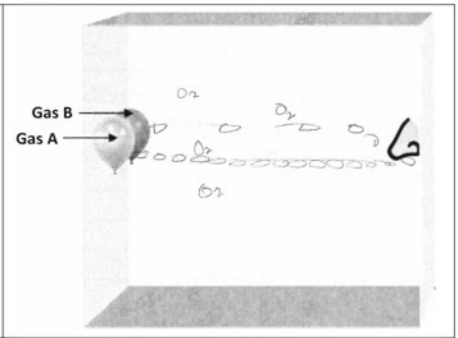
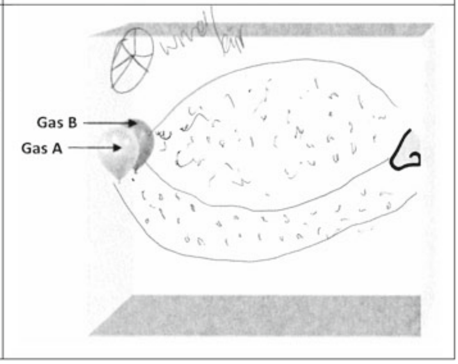
a *Part of a first-year university physics student's drawing in response to Question 3. The student wrote, "O_2 would bond quicker to C_2H_7N because there are more available bonds, making C_2H_7N move faster." Structure of solvent: Macroscopic/microscopic; Origin of solute motion: 2; Solute particle trajectories: 1*	
b *Part of a high school chemistry honors student's response to Question 3. The student wrote, "Gas B has more hydrogen and carbon, so it's likely that the smell will be a lot stronger than Gas A." Structure of solvent: Macroscopic; Origin of solute motion: 1; Solute particle trajectories: 1*	

Fig. 4 Examples of student responses to Question 3 in the SAMM survey (see Table 1 for scenario). Students are asked to draw Gas A and Gas B perfume molecules and their movements, soon after the balloons are popped, to explain their answers. Note: Gas A was CH_5N, and Gas B was C_2H_7N. *Scores* (refer to Table 3 and the text describing it) indicate the thinking patterns exhibited in the student's entire response to the survey (based on consistency across all items, see Table 2) for the structure of solvent, origin of solute motion, and solute particle trajectories progress variables. The *numbers* shown with each example refer to the categories of thinking patterns described in the text for the last two of these progress variables.

5. *Solute molecules are always in motion and that motion is an intrinsic property of the molecules*. Students with this thinking pattern explicitly express that molecules are in constant motion, and they do not attribute the motion to features of the molecules. This view is closest to the *intrinsic-dynamic* IA.

Second, we describe our *trajectories of particles* progress variable, which was not identified in the initial LP. We observed nine distinguishable categories of the application of IAs along this progress variable, all of which include combinations of IAs in the structure and dynamics dimensions:

1. *Solute particles do not move by themselves*; *the air controls their trajectories*. Students with this view indicate that without air or external forces, the solute particles would not move. Students talk about solute movement only in terms of solvent (air) movement, sometimes explaining that solute particles are bonded to

air and that is how they can move. This view is an application of the *static* IA about dynamics and *continuous* IA about structure.

2. *Solute particles move*; *the air controls their trajectories*. Students explicitly recognize that the solute particles move by themselves, and that the air or some outside force controls where they go. This view applies aspects of the *causal-dynamic* IA about particle dynamics and an *embedding* IA about structure.
3. *Solute particles move*, *but it is not clear how*, *and the air might influence the trajectories of solute particles*. In this thinking pattern, students also explicitly recognize that solute particles move by themselves, but they indicate the trajectories that solute particles take. Motions may include straight lines, parabolic trajectories, rising toward the ceiling, and rolling along the floor. Some students indicate that air currents, breezes, or wind influences (i.e., helps) solute particles' trajectories. This relates to the *causal-dynamic* IA about particle dynamics and perhaps represents a transition from an *embedding* to a *vacuum* IA about structure.
4. *Solute particles travel by avoiding macroscopic obstacles*, *and the air might influence their trajectories*. In this thinking pattern, students consider the solute as particulate and independently moving, but everything else as macroscopic and object-like, such as air masses or regions of different density. Again, some students indicate ways that air, or forms of it, influences or helps the motion of solute particles. This relates to the *causal-dynamic* IA about particle dynamics and presents a mixture between the *continuous* and *embedding* IAs of structure.
5. *Solute particles radiate outward from the source*, *and the air might influence trajectories of particles*. Students with this view draw and describe the solute as radiating outward in all directions. Some students indicate that air currents, breeze, or wind influences this radiation. Although this leads to the conclusion that the solute concentration spreads from the source, the solute is considered as something between *continuous* and *embedded* in the solvent, while the particle dynamics are considered *causal-dynamic*.
6. *Solute particles collide with other particles*, *but air controls the particle trajectories*. In this thinking pattern, students consider solute as particulate and the solvent (air) as continuous. They describe solute particles being controlled or guided, in some cases by floating in fluid-like air and in other cases by being drawn by a force, such as the nose drawing breath and pulling the air toward it. This has aspects of *static* and *embedding* IAs about structure and *causal-dynamic* IA about particle dynamics.
7. *Solute particles have random trajectories*, *except that they never collide with other particles*; *and air might influence solute particle trajectories*. Students with this view draw solute particles with curvy, wiggly, or loopy trajectories (not straight lines) going in all directions. They describe the solute particles as having no specific destination but eventually reaching the nose. Some students draw solute particles avoiding air particles, indicating a reason for the wiggly trajectories, thereby indicating that the solvent influences the trajectories of solute particles. This view of solute particle trajectories considers both solute and solvent as relying on close to a *vacuum* IA, with particle dynamics having aspects of *causal-dynamic* and *contingent-dynamic* IAs.

8. *Solute particle trajectories occur in straight lines and are based on collisions with air particles*; *however*, *the air particles are the source of energy for the solute particles to move*. Students with this thinking pattern draw collisions between solute and air particles, and they either show that air particles actively push the solute particles along or they describe solute particles as receiving energy from the air particles. This relates to the *contingent-dynamic* IA about particle dynamics, and a *vacuum* IA about structure.
9. *Solute particles collide with other particles* (*air and solute*) *as they move randomly in straight-line motion*, *and air might influence the trajectories of solute particles*. This view is closest to the most scientifically accurate model that students display, with students consistently describing properties as emergent from random particle-level motions, regardless of external conditions (i.e., temperature) or particle-level variations (e.g., size/mass of solute particle). Some students describe features of air, or currents or wind, as influencing solute particle trajectories. This view relates to the *vacuum* IA about structure and an *intrinsic-dynamic* (or sometimes *contingent-dynamic*) IA about particle dynamics.

Distributions of Thinking Patterns in Each Progress Variable Across Schooling Levels

Although the categories of thinking patterns that the SAMM survey identifies are generally organized from more novice to more sophisticated, it is not expected that students progress through them in that order. Rather, as described elsewhere, we determined that certain combinations of categories in the three different progress variables turn up consistently in a limited number of fairly well-defined mental models that students exhibit (Stains and Sevian 2013), and that there is variation in the sophistication of IAs in each mental model. As we discuss below, our results suggested that the IAs that students recently practiced in school tended to turn up in students' thinking patterns, and conversely when students did not practice with using certain IAs, the IAs tended not to turn up as readily.

For the two progress variables whose categories of thinking patterns are described above, it is likely that the null hypothesis can be rejected in both cases. That is, it is likely that the level of schooling and thinking pattern are not independent. For origin of motion, $\chi^2(18, 308) = 50.76$, $p < .05$. For solute particle trajectory, $\chi^2(42, 308) = 73.77$, $p < .05$. Shown in Figs. 5 and 6 are the distributions of thinking patterns seen in the two progress variables, broken out by level of schooling.

Several schooling levels exhibited distributions of thinking patterns in both progress variables that display significant differences from random distributions. Statistically significant differences (lower or higher than expected) included:

- Middle school students: Regarding trajectories, fewer students than expected demonstrated category 3 (solute moves but not clear how), and more than expected demonstrated category 8 (trajectory based on collisions with air particles, but air particles provide the force for solute particle to move).

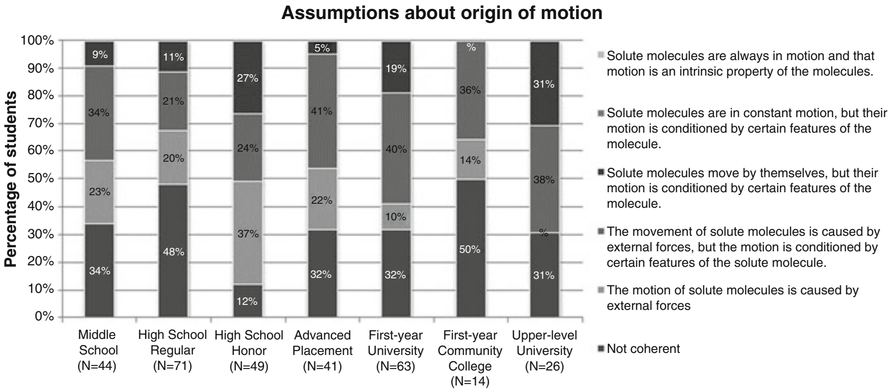


Fig. 5 Distribution of categories of thinking patterns about origin of motion of solute particles by level of schooling

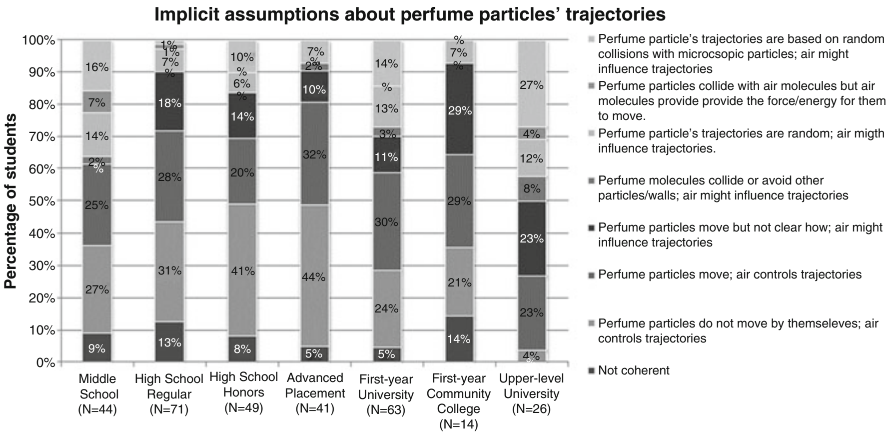


Fig. 6 Distribution of categories of thinking patterns about trajectories of solute particles by level of schooling

- High school regular students: More students were inarticulate about solute origin of motion than expected. Fewer students than expected held category 9 about trajectories (based on random collisions).
- High school honors students: Regarding origin of motion, fewer students were inarticulate, and more students had categories 1 (motion caused by external forces) and 3 (motion conditioned by certain properties) than expected.
- Upper-level university students: Regarding origin of motion, fewer students held category 1 (motion caused by external forces), and more held category 3 (motion conditioned by certain properties), than expected. For trajectories, fewer students held category 1 (solute does not move, air controls trajectory), and more students held category 9 (based on random collisions), than expected.

Interpretation of Distribution Results in the Context of the Curriculum

These differences are likely to be able to be explained by what and how students are learning in school. As indicated earlier, we deliberately selected a phenomenon (diffusion in a gaseous mixture) that is not explicitly taught in the curriculum in any of the classes from which students participated in the study. It is to be expected that upper-level university students would exhibit greater acquisition of the most sophisticated IAs. However, middle school students demonstrated greater sophistication in IAs than expected. The school district from which the middle and high school students participated includes in its eighth grade curriculum one-third of the year in the science course focused on molecules and their movement (Lawrence Hall of Science 2006). In contrast, at the high school level, the curriculum focuses on more quantitative descriptions of matter. Since the instrument measures IAs that constrain reasoning using mental models that students conjure instantaneously in response to a generative question, it makes sense that the mental models of middle school students would be more likely to be based on IAs that students had recently practiced using. This points to our earlier assertion that LPs are not independent of the conditions of learning, as recent experiences of students, particularly formal learning in which students practice using specific IAs, were translated into how students think about a phenomenon. It underscores the need to take into account curricular and instructional conditions in continuing study of this LP.

The data are cross-sectional, not longitudinal. That is, these are not data from the same students measured across time. However, it is possible to ascertain that there is not one clear "progression" of thinking patterns through sophistication of IAs. We also find in subsequent analysis that there is not a clear organization of mental models in order of increasing sophistication (Stains and Sevian 2013). Nearly every category in each progress variable was observed at each educational level, as shown in Figs. 5 and 6, and is to be expected unless there is some developmental reason why certain kinds of reasoning would be unusual at particular ages. More interestingly, specific IAs turned up more consistently in students whose curriculum involved more deliberately planned practice with using those assumptions. This is consistent with a concern raised by Sikorski and Hammer (2010), that LPs may not be so easily organized into a clear pathway of levels proceeding from less to more sophisticated. A logical next step with this work is to conduct a longitudinal study that tracks a group of students over several years, taking into consideration the IAs students work with specifically in the curriculum.

Discussion and Implications

An aspect of research-based best practices in formative assessment already includes determining the IAs students operate under as they reason (Black et al. 2003). Instructional decisions should capitalize on this and include efforts to challenge less sophisticated IAs and to give students deliberate, consistent, and coherent practice in using more sophisticated IAs in reasoning. The cycle of validation of a structure of matter LP presented in this chapter suggests that when students practice using specific assumptions, they exhibit thinking patterns that include those assumptions more often than expected from a random distribution. In particular, when the youngest students in our study practiced using some of the most sophisticated assumptions to explain and predict natural phenomena involving matter, they developed more sophisticated ways of thinking. Thus, this suggests that deliberately planned explicit practice with more sophisticated assumptions that is consistent and coherent over many years could result in robust and more scientifically accurate content knowledge. This is in harmony with a recommendation reached by Rappoport and Ashkenazi (2008) that consistent long-term practice by students with emergent reasoning (where the mechanisms occurring at the particle level account for phenomena observed at the laboratory level) would tend to improve the situation of students using submergent reasoning (where atoms and molecules are assumed to behave as objects at the laboratory level do) to explain and predict scientific phenomena in which the properties of matter are of concern.

Theory argues in favor of the most difficult conceptual changes involving the restructuring of knowledge, that is, paradigm shift. The results from our study show that IAs constrain the patterns of thinking that students exhibit, so it is probably the case that some IAs have a stronger constraining power than others. In our study, although we did not collect data on the fraction of students in high school who were in the same school district in middle school, we know that a large fraction of the students attended middle school in this district, and that their 8th grade science course included one-third of the year in the same curriculum that the 8th grade students in our study learned from. It is also the case that, in this school district, the high school science curriculum focuses on increasingly quantitative (perhaps algorithmic) aspects and does not include much explicit practice in using the more scientifically accurate assumptions about the structure and motion of matter at the particle level (i.e., the vacuum assumption about matter and the random intrinsic motion assumption about the movement of particles). This suggests that when there is not deliberate coherence and reinforcement of the use of these assumptions, students' conceptual understanding does not include the assumptions.

Interpreting this in light of conceptual change theories would affirm that somewhere among this set of assumptions there is at least one paradigm shift in conceptual understanding that is difficult to achieve. However, our results also support the notion that paradigm shift appears to involve changes in *which* assumptions are applied when reasoning. For example, in one theory framing the structure of conceptual understanding and how change occurs, Chi and collaborators (Chi 2005; Chi et al. 1994) argue that the most difficult conceptual changes are ones that involve shifting the ontological categories to which understanding is assigned. According to this approach, ontological categories of conceptual understanding (e.g., things vs. processes vs. mental states) are considered to be both mutually exclusive and static (except during moments of radical conceptual change). Gupta et al. (2010) have challenged this, however, showing that both expert and novice reasoning can traverse ontological categories of conceptual understanding in ways that are productive.

Combining this, then, with what we have been able to show about how students rely on IAs, we contend that the process of developing more scientifically accurate conceptual understanding might well be viewed as a process of learning to qualify assumptions, that is, learning is a process of acquiring facility with more assumptions and knowing when the conditions are appropriate to apply particular assumptions one holds in a rich repertoire of assumptions. We see this as related to how Wiser and Smith describe conceptual restructuring as, "different aspects can be foregrounded in different contexts" (Wiser and Smith 2008, p. 207).

While some researchers have argued to distance conceptual change theories from the study of mental models (Greca and Moreira 2000), our approach argues in favor of building constructively from the intersection between these pursuits. As Greca and Moreira point out, when mental models are built deliberately through instruction, they are translations in learners' minds of "logically clear" and "specially designed" conceptual models that instruction and instructional materials attempt to help students to develop so that they can be used in explaining, predicting, and otherwise reasoning about scientific phenomena and objects. Vosniadou (2002), meanwhile, argues that when generatively instigated, a mental model is a representation of a person's conceptual understanding. Although these are two mechanisms for causing the formation and use of mental models, it is reasonable to expect that the mental models function similarly for the person who holds them. To the extent that a conceptual model (of instruction) is scientifically accurate, a goal of instruction therefore is to aid the student in developing a robust understanding of and ability to use a conceptual model (which, presumably, is productive, even if it has some scientific inaccuracies). Students translate their conceptual understanding into a mental model as they reason, and IAs form a filter that constrains this translation. Likewise, it is reasonable to presume that the same IAs filter how students incorporate what they learn (i.e., conceptual models) into their conceptual understanding. Being able to identify the IAs, then, gives both curriculum and instruction more power to design interventions to advance learners toward developing more scientifically accurate understanding that will be robust and can make use of productive intermediate understandings, or stepping stones, and avoid unproductive intermediate understandings. Furthermore, in alignment with the argument made by Sikorski and Hammer (2010), in their critique of how LP work tends to treat progress simply in terms of monotonically increasing advances in sophistication, conceptual understanding can defy organization into levels that can be compared to scientifically correct understanding, because that understanding is only a part of the complex ecology of conceptual knowledge.

Conclusion

We have illustrated an approach in which we begin with a hypothetical LP drawn from a synthesis of many studies of how students think about the nature of matter, that describes differences between specific IAs that can be used, often productively, as learners develop conceptual understanding. We then developed a mechanism for capturing the distinct thinking patterns that result from the constraints imposed by combinations of specific IAs, and in analysis of the thinking patterns, we are able to observe evidence of the application of the IAs. Furthermore, we were able to clarify the progress variables along which the IAs operate. We showed that this process of validation can be productive in refining an LP whose progress variables are characterized by IAs. In particular, we showed that the structure and motion of matter may be more accurately described by three progress variables (particle-level structure of the material, origin of motion of particles in the material, and trajectories/motions of particles in the material) than by the two progress variables in the initially assumed hypothetical LP (particle-level structure and dynamics). Because conceptualizing chemistry understanding provides a way of bringing coherence to many patterns of reasoning observed in students, and because IAs can be useful in characterizing students' thinking patterns, this approach may hold promise for tracking the progress of learning along an LP. We hope that this approach may enable tracking the progress of learning without compromising the progress that research in science education has made in understanding the complex ecologies of learners' understanding and reasoning. Specifically, we hope our approach can enable (1) determining pathways that are most efficient in transitioning students from less toward more scientifically accurate conceptual understanding and (2) testing whether specific instructional and curricular interventions (with deliberate IAs practiced and specific sequences and combinations of them) are effective in doing so.

Our example demonstrating one cycle of validation in refining an LP about the structure of matter provides evidence that IAs can be identified. Based on this, we conjecture that changes in students' use of IAs can also be detected. Measuring changes in the application of IAs could be a useful indicator that conceptual changes may have occurred.

Acknowledgments This chapter is based on work supported by the US National Science Foundation (NSF), while one of the authors (HS) was working at the Foundation, under her Independent Research and Development plan approved by the agency, and as part of an internal portfolio analysis to study NSF's footprint on learning progressions research. The SAMM study described in this work was also supported, in part, by NSF award EHR-0412390. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

References

Alonzo, A., & Steedle, J. T. (2009). Developing and assessing a force and motion learning progression. *Science Education, 93*(3), 389–421.

Black, P., Harrison, C., Lee, C., Marshall, B., & Wiliam, D. (2003). *Assessment for learning: Putting it into practice*. Berkshire: McGraw-Hill Education.

Brown, D. E., & Hammer, D. (2008). Conceptual change in physics. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 127–154). New York: Routledge.

Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *The Journal of the Learning Sciences, 14*, 161–199.
Chi, M. T. H., Slotta, J. D., & de Leeuw, N. (1994). From things to processes: A theory of conceptual change for learning science concepts. *Learning and Instruction, 4*, 27–43.
Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher, 32*(1), 9–13.
Collins, A., Joseph, D., & Bielaczyc, K. (2004). Design research: Theoretical and methodological issues. *The Journal of the Learning Sciences, 13*(1), 15–42.
de Vos, W., & Verdonk, A. H. (1996). The particulate nature of matter in science education and in science. *Journal of Research in Science Teaching, 33*(6), 657–664.
Design-Based Research Collective. (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher, 32*(1), 5–8.
diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*(2–3), 105–225.
Duschl, R., Maeng, S., & Sezen, A. (2011). Learning progressions and teaching sequences: A review and analysis. *Studies in Science Education, 47*(2), 123–182.
Greca, I. M., & Moreira, M. A. (2000). Mental models, conceptual models, and modelling. *International Journal of Science Education, 22*(1), 1–11.
Gupta, A., Hammer, D., & Redish, E. F. (2010). The case for dynamic models of learners' ontologies in physics. *The Journal of the Learning Sciences, 19*(3), 285–321.
Jin, H., & Anderson, C. W. (2012). Developing assessments for a learning progression on carbon-transforming processes in socio-ecological systems. In A. C. Alonzo & A. W. Gotwals (Eds.), *Learning progressions in science* (pp. 151–182). Rotterdam: Sense Publishers.
Johnson, P. (1998). Progression in children's understanding of a "basic" particle theory: A longitudinal study. *International Journal of Science Education, 20*(4), 393–412.
Johnson, P. (2005). The development of children's concept of a substance: A longitudinal study of interaction between curriculum and learning. *Research in Science Education, 35*(1), 41–61.
Johnson, P., & Tymms, P. (2011). The emergence of a learning progression in middle school chemistry. *Journal of Research in Science Teaching, 48*(8), 849–877.
Kelly, A. E. (2004). Design research in education: Yes, but is it methodological? *The Journal of the Learning Sciences, 13*(1), 115–128.
Kind, V. (2004). *Beyond appearances: Students' misconceptions about basic chemical ideas* (2nd ed.). London: Royal Society of Chemistry.
Lawrence Hall of Science. (2006). Chemical interactions. In *Full option science system for middle school*. Berkeley: Lawrence Hall of Science.
Mislevy, R. J., Steinberg, L. S., Breyer, F. J., Almond, R. G., & Johnson, L. (2002). Making sense of data from complex assessments. *Applied Measurement in Education, 15*(4), 363–389.
Mohan, L., Chen, J., & Anderson, C. W. (2009). Developing a multi-year learning progression for carbon cycling in socio-ecological systems. *Journal of Research in Science Teaching, 46*(6), 675–698.
Nakhleh, M. B. (1992). Why some students don't learn chemistry: Chemical misconceptions. *Journal of Chemical Education, 69*(3), 191–196.
National Council of Teachers of Mathematics. (2010). *NCTM public comments on the common core standards for mathematics*. Retrieved May 29, 2011, from http://www.nctm.org/about/content.aspx?id=25186
National Research Council. (2001). *Knowing what students know: The science and design of educational assessment.* Committee on the Foundations of Assessment. J. Pelligrino, N. Chudowsky, & R. Glaser (Eds.). Board on Testing and Assessment, Center for Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.
National Research Council. (2007). *Taking science to school: Learning and teaching science in grades K-8.* Committee on Science Learning, Kindergarten through Eighth Grade. R. A. Duschl, H. A. Schweingruber, & A. W. Shouse (Eds.). Board on Science Education, Center for Education. Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas.* Committee on a conceptual framework for New K-12 Science Education Standards. Board on Science Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

President's Council of Advisors on Science and Technology. (2010). Report to the President: *Prepare and inspire: K-12 Education in Science, Technology, Engineering and Math (STEM) for America's future*, September 2010 Prepublication version, Washington, DC. Retrieved May 29, 2011, from http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-stemed-report.pdf

Rappoport, L. T., & Ashkenazi, G. (2008). Connecting levels of representation: Emergent versus submergent perspective. *International Journal of Science Education, 30*(12), 1585–1603.

Salinas, I. (2009, June). *Learning progressions in science education: Two approaches for development*. Paper presented at the Learning Progressions in Science (LeaPS) conference, Iowa City. Available from http://www.education.uiowa.edu/projects/leaps/proceedings/

Scheffel, L., Brockmeier, W., & Parchmann, I. (2009). Historical material in micro-macro-thinking: Conceptual change in chemistry education and in the history of chemistry. In J. Gilbert & D. Treagust (Eds.), *Multiple representations in chemical education* (pp. 215–250). Berlin: Springer.

Sevian, H., & Anderson, C. W. (2012, March 29). *Using learning progressions to improve science teaching and learning*. Short course presented at the National Science Teachers Association Conference, Indianapolis.

Sikorski, T.-R. & Hammer, D. (2010, June 29–July 2). A critique of how learning progressions research conceptualizes sophistication and progress. In *Proceedings of the 9th International Conference of the Learning Sciences* (pp. 1032–1039), Chicago.

Stains, M., & Sevian, H. (2013). Uncovering implicit assumptions: A large-scale study on students' mental models of diffusion. Manuscript submitted for review.

Stains, M., Escriu-Suñé, M., Molina Alvarez, M. L., & Sevian, H. (2011). Assessing secondary and college students' understanding of the particulate nature of matter: Development and validation of the structure and motion of matter (SAMM) survey. *Journal of Chemical Education*, forthcoming.

Taber, K. S., & García Franco, A. (2010). Learning processes in chemistry: Drawing upon cognitive resources to learn about the particulate structure of matter. *The Journal of the Learning Sciences, 19*(1), 99–142.

Talanquer, V. (2006). Common sense chemistry: A model for understanding students' alternative conceptions. *Journal of Chemical Education, 83*(5), 811–816.

Talanquer, V. (2009). On cognitive constraints and learning progressions: The case of structure of matter. *International Journal of Science Education, 31*(15), 2123–2136.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*(1), 45–69.

Vosniadou, S. (2002). Mental models in conceptual development. In L. Magnani & N. J. Nersessian (Eds.), *Model-based reasoning: Science, technology, values*. New York: Kluwer.

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth – A study of conceptual change in childhood. *Cognitive Psychology, 24*(4), 535–585.

Wilson, M. (2009). Measuring progressions: Assessment structures underlying a learning progression. *Journal of Research in Science Teaching, 46*(6), 716–730.

Wiser, M., & Smith, C. L. (2008). Learning and teaching about matter in grades K-8: When should the atomic-molecular theory be introduced? In S. Vosniadou (Ed.), *The international handbook of research on conceptual change* (pp. 205–239). New York: Routledge.

Wiser, M., Smith, C. L., & Doubler, S. (2012). Learning progressions as tools for curriculum development: Lessons from the inquiry project. In A. Alonzo & A. Gotwals (Eds.), *Learning progressions in science* (pp. 359–404). Rotterdam: Sense Publishers.

At the Beginning Was Amount of Material: A Learning Progression for Matter for Early Elementary Grades

Marianne Wiser, Kathryn E. Frazier, and Victoria Fox

Introduction

One of the most important contemporary scientific theories, the atomic-molecular theory, is also one of the hardest to learn. However, students' difficulties might be less with the theory itself than with the incompatibility between the atomic model and students' ideas about matter and its behavior at the *macroscopic* and *microscopic*[1] scale (Smith et al. 2006). Conceptual analyses of students' difficulties with scientific ideas about matter at the macroscopic, microscopic, and nanoscopic levels suggest that a sound macroscopic and microscopic understanding of matter would facilitate learning the atomic-molecular theory (AMT) and therefore should be a central goal for science education in elementary and middle school (Smith et al. 2006; Wiser and Smith 2009).

Not surprisingly, young children's ideas about matter and its transformations are incommensurable, at least in the weak sense, with scientists'. Perhaps more surprising is the ample evidence from research suggesting that many middle school students are not conceptually much closer to scientific understanding. For example, many sixth graders believe that very small pieces of any material and big pieces of some materials (such as Styrofoam) have no weight because "they feel like nothing" (Smith et al. 2005; Smith 2007). This belief alone makes the atomic model problematic for students: if tiny things weigh nothing, matter cannot be made exclusively of atoms. Indeed, many students envision atoms as embedded in "stuff" (Lee et al. 1993). The idea that tiny things weigh nothing is not a simple false belief,

[1] "Microscopic" refers to entities that are invisible to the naked eye but can be seen with a light microscope.

M. Wiser (✉) • K.E. Frazier • V. Fox
Psychology Department, Clark University, Worcester, MA, USA
e-mail: MWiser@clarku.edu

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_5,

easily dispelled by demonstrating they actually do. Rather, this is a belief stemming from students' concept of weight and related concepts, as well as their epistemological stance that the unaided senses tell the truth.

Revising this belief is part of a broad *reconceptualization* of matter and its behavior at the macroscopic and microscopic levels. By "reconceptualization" we refer to a deep and fundamental reorganization of the large network of knowledge relevant to understanding matter. If such reconceptualization takes place, students' understanding becomes compatible with the scientific theory and amenable to further reconceptualizations. In middle school, they will be able to learn to interpret matter and its behavior at a particulate level and eventually at the atomic-molecular level. For too many students however, the conceptions developed in childhood are never revised productively, suggesting that one needs to rethink how to teach about matter in elementary school. What kind of curriculum could foster such reconceptualization and prepare students to learn AMT?

Our answer is a curriculum based on a *learning progression for matter*. As articulated by Corcoran and colleagues, "Learning progressions in science are empirically-grounded and testable hypotheses about how students' understanding of, and ability to use, core scientific concepts, explanations and related practices grow and become more sophisticated over time, *with appropriate instruction*. These hypotheses describe the pathways students are likely to follow to the mastery of core concepts. They are based on research about how students' learning actually progresses—as opposed to selecting sequences of topics and learning experiences based only on logical analysis of current disciplinary knowledge and on personal experiences in teaching" (Corcoran et al. 2009).

Several research teams are working on developing learning progressions for matter for different grade bands (see, e.g., Delgado and Krajcik 2010; Johnson 1998, 2005; Smith et al. 2006; Stevens et al. 2010; Wiser et al. 2012). We and our colleagues at TERC; the University of Massachusetts, Boston; and Tufts University are focusing on the elementary grades. We refer to the K-5 learning progression as LPM (learning progression for matter). LPM describes how elementary school students' knowledge about matter could become scientifically sound and support learning AMT later on.

LPM is what Krajcik and his colleagues label a "*theoretical* learning progression" (Stevens et al. 2009). Developing it starts with conceptual analyses of the sources of difficulties experienced by students while learning the scientific theory from traditional curricula. On the basis of those analyses, an alternative *hypothetical* path for learning is generated, one in which a series of conceptual changes would progressively and productively transform students' knowledge, making it more and more compatible with the scientific theory. LPM is *virtual* as it cannot unfold without a curriculum of its own that will support knowledge restructuring. As with any hypothesis, we will not know whether LPM is an effective path to scientifically sound understanding of matter until we watch it successfully unfold in students (Wiser et al. 2012). In other words, if an LPM-based curriculum brings students closer to a scientific understanding of a domain than do school curricula already in place, LPM is supported. Empirical findings lead to revisions of both LPM and curriculum, starting a new cycle.[2]

Where a learning progression (LP) ends and where curricula begin is one of the issues being debated in the learning progression community (e.g., see Foster and Wiser 2012). It is generally agreed that LPs act as guides to curriculum development. LPs broadly define learning experiences that are key to reconceptualization, while curricula specify the content and order of learning experiences at a much finer grain. However the more sensitive a researcher is to the constraints on individual conceptual changes and to the number of new/revised pieces of knowledge involved in the reorganization of even a portion of the knowledge system, the more specific (and specifically ordered) key learning experiences in an LP become. This chapter reflects our own view that it is very difficult to disentangle the two, and, therefore, we will not maintain a strict boundary between LPM and LPM-based curriculum.

LPM and LPM-Based Curricula: General Considerations

LPM is first and foremost *cognitively based*: where ideas about matter "come from," and how they could progressively change, become more complex and integrated, apply to wider ranges of phenomena, and be linked to those phenomena by a more sophisticated epistemology, are established on conceptual grounds. LPM is organized around *core concepts*. Core concepts are not just the concepts involved in defining matter scientifically (e.g., mass). They are also concepts, such as weight, that play a conceptual role in students' progressing toward scientific understanding. Similarly successive states of the knowledge network are not pieces or simplifications of the scientific theory but rather knowledge states that get *conceptually* closer to it.

Using Anderson's terminology (Mohan et al. 2009), we will refer to young children's ideas as LPM's *lower anchor*. The knowledge about matter targeted at the end of 5th grade could be called LPM's *upper anchor*. However, taking a longer term view, LPM is part of a K-12 matter LP for which the upper anchor is AMT. Thus, we prefer thinking of the end point of LPM as the *Grade 5 stepping stone* toward AMT. We will also refer to the state of the system at the end of Grade 2 as the *Grade 2 stepping stone*. To assist the reader in reading the subsections below, Table 1 summarizes the ways we elaborated LPM, referring to the theoretical constructs core concept, lower anchor, stepping stone, and lever concept (lever concepts

[2]The idea that learning progressions are hypothetical and revisable is not universally accepted. Some LPs are purely empirical: they consist of a series of stages ordering students' beliefs from less to more scientific according to certain criteria (e.g., the level of integration of different principles). The knowledge changes captured by those learning progressions are effected by curricula currently in place. (See, e.g., Liu and McKeough 2005.) This type of LP is not revisable; its consequential validity and the sense in which it is hypothetical are not entirely clear.

Table 1 Theoretical constructs in LPM

Theoretical construct	Brief characterization	Examples	Relation to other constructs
Core concepts	Concepts that are central (a) to the tenets of the scientific theory itself, or (b) to supporting the understanding, use, and/or learning of the scientific theory	Of (a): matter, mass, volume, density, states of matter (for later grades: pure substance, mixture, element, compound, atom, molecule, bond) Of (b): material, weight, particle	Concepts are mental entities constituted of many kinds of beliefs (e.g., beliefs about what invariants they refer to in the world and how they are related to other concepts in laws, explanations, and generalizations about phenomena)
	Core concepts provide vertical continuity and horizontal coherence to the LP Both types of core concepts (a) and (b) are core throughout the whole LP, although their content and the relations among them are different in different grade bands. They may exist only in precursor form in the earlier grades		Important concepts are often symbolized in language with single words so that beliefs involving those concepts can be expressed with sentences. Relations among scientific concepts are also expressed with the language of mathematics
Lever concepts	A temporary status of some core concepts. Core concepts have the status of lever concepts when they play a key role in curriculum and learning at certain points in time. Lever concepts for a grade band are core concepts that, at that time, (a) already have a rich content; (b) need revising and can be productively revised; and (c) promote the revision or introduction of other concepts	Object, non-solid, and size (for grades K–2) Material, amount of material, weight, and size (for grades 3–4)	Some lever concepts in some grade bands are core concepts (b) (e.g., weight) and others are core concepts (a) (e.g., objects and non solids, heavy for size)
	How long a core concept remains a lever depends on how long the reconceptualization(s) of which it is part take(s)	Solid and liquid materials, volume, and heavy for size (for grade 5)	Lever concepts drive the reconceptualizations necessary to reach stepping stones

will be introduced later in the chapter). Table 2 presents a synopsis of the core concepts in the lower anchor, the Grade 2 stepping stone, and the Grade 5 stepping stone.

Stepping Stones

The conceptual changes in LPM are progressive; they happen in small steps. However, after a series of conceptual changes, the knowledge network reaches a new state of (relative) equilibrium: a stepping stone. Its content and structure are radically different from the previous stepping stone (or the lower anchor) and support explanatory accounts of matter and its behavior that are radically different from before. For example, compared to the Grade 2 stepping stone, the Grade 5 stepping stone includes new concepts (e.g., *heaviness for size*), generalized and systematized principles (e.g., many materials exist in solid and liquid form), and radically revised concepts (*matter*), as well as multiple new relations among concepts. Another essential feature of a stepping stone is that it is conceptually closer to the scientific theory. From a top-down point of view, a stepping stone may look quite "unscientific." For example, the concept of matter in the Grade 2 stepping stone prominently includes the belief that matter is visible and touchable. And yet, as we will argue below, the Grade 2 stepping stone is conceptually closer to the scientific theory than the lower anchor.

Translating LPM into a curriculum is also a cognitive enterprise. We use LPM's stepping stones as learning goals for the different grade ranges. Which core concepts, and which relations among those core concepts, should be foregrounded in each grade range are also conceptually based decisions. Finally, we elaborate LPM's key learning experiences into curricular units that target specific conceptual changes. To frame our work on teaching matter in early elementary school, we will first present the core concepts, lower anchor, and stepping stones in LPM.

Core Concepts

Core concepts in LPM are of two kinds. Some are central to the scientific theory (e.g., matter, mass, volume, density, states of matter, and phase changes). Others are not part of the tenets of scientific theory but are core in a *cognitive* sense: they are necessary to make sense of the theory and to use it (e.g., weight is used to measure mass). These concepts are also core in a developmental and learning sense: students need to construct scientifically compatible versions of these concepts before they tackle some of the tenets of the scientific theory. For example, the way to understanding that even tiny pieces of matter have mass (which is necessary to make sense of the atomic-molecular theory) is to first believe that they have weight (see Foster and Wiser 2012, for a justification of this claim). How one establishes the concepts that are *cognitively* core for a particular domain is beyond the scope of this

Table 2 LPM synopsis

	Lower anchor (kindergarten)	Grade 2	Grade 5
Core concepts (Lever concepts are in italics)	**Precursor of material**	***Material***	***Material***
	Know the names of some liquids and solid materials	Apply the material construal and the object construal to both objects and non-solid samples	Extend notion of materials to include **gaseous materials** (air, water vapor)
	Have great difficulty applying the material construal to solid objects	Know the names of many materials	Understand that some materials can be in ***solid, liquid,*** or **gaseous form** (e.g., ice, water, water vapor)
	Associate some intensive properties (smell, taste, hardness, brittleness) with some materials	Material as an explicit concept: "**made of**" differentiated from "**made from**"—"made of X" means constituted of little pieces of X	Differentiate material from state of matter
		Materials have specific (intensive) properties	Reliable properties of material include melting point and boiling point
		Material identity is conserved when a solid is ground	
		Some (familiar) materials keep their identity when they melt/freeze	
	Weight	***Weight***	***Weight***
	Measured by hefting	Solid objects and non-solid samples have weight	Extensive (i.e., proportional to amount of material)
	Some objects are heavy; others are light. Not all objects have weight (e.g., tiny things, Styrofoam, balloons)	Weight measured with a scale; differentiated from heft	"Heavy object" differentiated from "heavy kind of material"
	Changes when shape changes (because object identity changes—e.g., ball to pancake shape)	Weight is invariant across shape change, cutting into large pieces, and grinding	Invariant across phase change

	Liquids and powders do not (necessarily) have weight	Bigger objects are heavier than smaller objects made of the same material	Gases have weight
		Adding and removing material changes weight	Any piece of material, however small, **visible** or **not**, has weight
			Use invariance of weight across phase change as evidence that no material has been gained or lost
	Precursor of amount of material	***Amount of material***	***Amount of material (mass)***
	Bigger objects have "more" [material name]	Quantify amount of material	Weight proportional to amount of matter. Amount of matter quantified across different materials
	Adding stuff makes it "more [material name]"	Associate weight with amount of material qualitatively	Conserve amount of matter across phase change
	Reshaping an object makes it "more/less [material name]"	Amount of material is invariant across reshaping and cutting into pieces	
Core concepts (Lever concepts are in italics)	***Size*/Occupying space**	***Occupying space***	***Volume***
	Lack geometric concepts of length, area, volume	Solid objects take up 3-D space	Granular and liquid materials occupy space
	"Bigness" is perceptually based and not explicitly differentiated into spatial dimensions. Big objects do not fit into small places and are hard to carry	Amount of non-solid displaced by an object is related (qualitatively) to the bigness of the object	Measure volume of liquid and granular materials
	Two solid objects cannot occupy the same space at the same time		Water displacement depends upon volume of submerged object, not weight
			Measure volume of solid objects using water displacement
			Differentiate different senses of volume (volume of material, space occupied by object, amount of empty space)
			Gases are compressible (i.e., volume depends on size of container)

(continued)

Table 2 (continued)

	Lower anchor (kindergarten)	Grade 2	Grade 5
	Heavy and light materials	**Weight associated with material**	***Heavy for size/density***
	Objects made of some materials are heavier than objects made of other materials (knowledge specific to some materials)	Objects made of some materials are heavier than objects made of other materials of the same size	Differentiate heavy object from heavy material
			Solid and liquid samples made of different materials are (more or less) heavy for size
			Gases are far less dense than solids and liquids
			Density of solids and liquids change with temperature
	Substantiality	***Substantiality***	**Matter**
	Solid objects and liquids can be touched and seen	Macroscopic pieces of solid and liquid material have weight	Any amount of liquid solid, liquid or gas, however tiny, visible or not, has weight and occupies space
		Macroscopic pieces of solid material occupy space	Gases are material in the same sense as solids and liquids
		Begin to see deeper similarities among solids, liquids, and granular materials	Matter has weight and occupies space
			Solids, liquids, and gases are forms of matter; some materials can exist in all three forms

chapter (see, e.g., Smith et al. 2006; Wiser and Smith 2008). However, these concepts tend to be ignored in science curricula.

It is important to keep in mind that the content of core concepts (like all concepts) changes over time. This change is often radical. Preschoolers, elementary school students, high school students, and scientists all have concepts of weight, number, and phase change, for example, but very different ones. In the next section, we outline what preschoolers' core concepts look like (i.e., the lower anchor) and how they need to change in order to become compatible with their scientific counterparts.

Lower Anchor

Precursors of Matter: Objects, Nonsolids, and Substantiality

Preschoolers have rich knowledge of objects and nonsolids. We hypothesize that reconceptualizing object, nonsolid, and the relation between the two is key to developing a concept of matter that includes all solids and liquids and excludes nonmaterial physical entities. This intermediate concept of matter can then be revised to include gases in late elementary school (Wiser et al. 2012).

Objects are a very salient part of children's physical world. Young children think of objects as individuated, permanent, and moving as a whole (Baillargeon 2002; Spelke 2000). They are sensitive to the size of objects and to their weight—or more specifically, to their heft (Smith et al. 1997)—and they know that the heavier of two objects placed on a balance scale will tip the scale (Metz 1993). They also think of objects as bounded and countable. Object boundaries are so salient that while children can count intact objects, they have extreme difficulty counting, for example, the number of forks when the forks are broken into two pieces (Sophian 2000).

Young children view nonsolids as more radically different from objects than adults do, especially scientists. For example, many young children say that liquids have no weight. Importantly they do not quantify nonsolids: when presented with 1 cup of sand in one box and 3 individual cups of sand in another box and asked "Which box has more sand?" 4-year-olds answer randomly (Huntley-Fenner et al. 2002). However, children do have a sense of *substantiality*, which encompasses objects and nonsolids: they expect that what they see can be touched and felt (Bower 1989; Spelke 1991; Bertenthal and Clifton 1998).

Precursor of Material: Nonsolids

Preschoolers do not conceive of objects as portions of material. Rather, they pay attention primarily to their shape, size, function, and individuality (Bloom 2000; Hall 1996). One way to describe this phenomenon is in terms of *construals*. Any object or situation can be perceived and interpreted in multiple ways—multiple construals can be applied to it. Preschoolers cannot yet apply a *material construal* to solid objects. Not surprisingly, they know very few names of solid materials. Those they know are labels for clusters of perceptual properties of objects, not for the kinds of stuff objects are *made of*. In other words, names of solid materials function as adjectives: “This is a steel spoon” means “This is a shiny, hard, grayish spoon” not “This spoon is shiny, hard, and grayish because it is made of steel.” Consequently, when a wood object is broken into pieces, 4- to 6-year-olds say that is wood but only if the pieces are big enough to have the same perceptual properties as the object (Smith et al. 1985). When wood turns into sawdust, they say it is not wood anymore because it is not hard and it is a different color, in other words, because it does not *look like wood*. In sorting tasks, they tend to group objects by shape and color rather than material and do not group aggregates with solids (Dickinson 1987; Krnel et al. 1998).

In contrast, preschoolers construe nonsolid samples in terms of materials. When asked “What’s that?” of an irregular shape made of an unfamiliar aggregate or gel, 4-year-olds produce names of substances or of substance properties (Hall 1996). Thus, it is likely that preschoolers’ concept of nonsolids is an important precursor to a scientific concept of material.

Amount of Material

While young children can correctly say that a large pile of sand is “more sand” than a small pile and know that if you add some sand to a pile you now have “more sand,” they fail at amount conservation. They say that amount changes when an object is reshaped (e.g., when a ball is flattened into a pancake (Piaget and Inhelder 1974)). Piaget proposed that children achieve amount conservation when they develop the logical ability to coordinate dimensions (e.g., the pancake is thinner, but it is wider than the ball). We disagree with this account and propose instead that young children do not yet have a *concept* of amount so that the very practice of coordinating dimensions is not considered relevant to the situation. In other words, the question “Is it the same amount?” is misinterpreted as a question about number, length, or area—quantities young children are familiar with. Evidence for this claim can be found in more recent studies using a different paradigm (e.g., Sophian 2000).

In most amount-related tasks, children are asked to identify which of two objects or groups of objects has more material. Failure at these tasks may be due in part to the ambiguity of the word “more” for young children. At an age where children’s understandings of amount and number are underdeveloped, questions invoking the use of the word “more” invite a number of diverse responses. One investigation of this hypothesis used three-dimensional objects and systematically varied amount, number, and individual size of the materials (see Fig. 1). Children (from low-income families) aged 4–6 performed significantly worse when the word “more” was used (i.e., “Which plate has more chocolate?” rather than “Which plate should this very hungry puppet choose to fill its belly with chocolate?”). However, very few succeeded at comparing amounts even when the word “more” was not used and would instead rely on individual size or number (Pradas 2010; Casey 2011; Wiser et al., 2011). Thus, children’s difficulties are conceptual as well.

Fig. 1 Testing children's concept of amount

In light of these recent findings, a domain-specific account of the development of amount of material (based on the conceptual development of number, material, and the quantification of amount of material) might be more valid than Piaget's domain general explanation in terms of logical abilities. We present such an account below.

Weight

For young children, weight is heft and is not correlated with amount of material—small things weigh nothing and neither do big pieces of materials such as Styrofoam (Smith et al. 1985). Young children expect the balance scale to reflect heft: if an object is judged heavier than another by heft, it is expected to tilt the balance scale (Metz 1993). Since weight is subjective, whether an object is heavy or not depends on who is holding it. For example, something can be light for an adult but heavy for the child (Smith et al. 1985). Finally young children say that weight changes when an object is reshaped (Piaget and Inhelder 1974). This is consistent with a concept of weight centered on heft, since the object does not feel equally heavy before and after reshaping.

Precursors of Volume

Young children have a concept of bigness that conflates length, area, and volume, and that is not quantified. Sensitivity to relative length and area is present from infancy although length and area quantification is difficult and long drawn (Sarama and Clements 2009; Lehrer et al. 1999). As to volume, children are aware that big things do not fit into small containers or through small holes (Smith et al. 1985) and they have known since infancy that two objects cannot occupy the same location at the same time and that a bigger object makes a bigger bump when it is covered by a blanket (Baillargeon 2002). However, those judgments are qualitative and are based on direct perception and action on objects. This is very different from having the concept that objects occupy a portion of 3-D space that can be quantified (Smith et al. 2010).

The concepts reviewed above are perceptually based and consistent with young children's epistemological stance that the unaided senses tell the truth and the world is the way it appears. These concepts also lack what is central to their scientific counterparts: amount is not quantified; weight is neither quantified nor correlated with amount; liquids and solids are ontologically different; bigness is a property of objects, not the extent of a part of 3D space; and "being material X" does not mean being constituted of material X. The differences between those concepts and their scientific counterparts are profound and hard to overcome. Although middle schoolers pass Piaget's ball and pancake task, use a balance scale properly, know that ice is frozen water, compute the volume of a cube, and can name many materials, their conceptual understanding of matter, liquids, solids, weight, material, and volume is often not radically different from that of kindergartners. For example, the majority of sixth graders in Carol Smith's studies say that if a piece of clay is repeatedly cut in half, the pieces will eventually weigh nothing and then cease to exist (Smith et al. 1997). For those students, the reconceptualization needed to align one's knowledge of matter at the macroscopic and microscopic levels with the scientific theory was incomplete at best. In the next section, we explore further the nature of this reconceptualization. We start with the Grade 2 *stepping stone* and then delve into the specific conceptual changes that constitute the reconceptualization from the lower anchor to the Grade 2 stepping stone.

Grade 2 Stepping Stone

In the Grade 2 stepping stone, solids and nonsolids have started to be integrated into an ontological category: things that can be seen and touched (a precursor of matter). Children now know that solid objects are made of many different kinds of materials, characterized by specific properties (e.g., smell, hardness[3]), and that different liquids are also different materials. For some familiar materials (e.g., water, chocolate, wax), children now know that material identity is maintained when solid samples are ground, melted, or frozen. Solid and liquid samples have weight, which is now distinguished from heft and is objective and extensive. Length and area are specific aspects of "bigness." Solid, liquid, and aggregate samples occupy space; (visibly) bigger samples occupy more space. Thus, the object construal and the material construal can be applied to both solid and liquid samples.

The Grade 2 stepping stone includes a quantified concept of amount of material and the conservation of amount of material when a solid or nonsolid sample is reshaped or divided into smaller samples. It also includes a (distant) precursor of density: "bigger objects are heavier than smaller ones made of the same material" and "objects of the same size made of different materials have different weight," making weight more cogently relevant to material identity.

The nexus of the Grade 2 stepping stone is a (*macroscopic*) *compositional model of material* (Fig. 2) in which a sample of material can be thought of as being made of a certain number of equal-sized pieces of that material. We hypothesize that the

[3] Hardness needs careful attention in the curriculum. It is a property young children are particularly sensitive to. However, unlike taste or smell, it is not preserved when a solid is ground or melted. Thus, young children could justify the idea that sawdust is not wood by arguing, "Wood is hard, this is not hard."

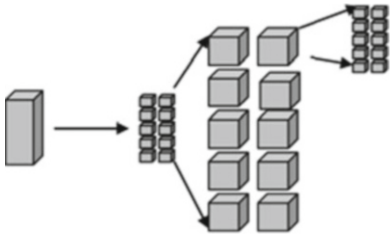


Fig. 2 Compositional model

compositional model underlies the understanding that objects are *constituted of* materials (the material construal of solids), the concept *amount of* material, and amount conservation. Note that the view of matter in this grade range is continuous rather than particulate. The compositional model is quite different from a particulate or molecular atomic model: it is not a model of the structure of matter but rather a quantification model.

Also note that the compositional model in the Grade 2 stepping stone involves *visible* pieces. A major aspect of the Grade 3–5 reconceptualizations will be coming to believe that matter can exist as microscopic pieces.

We will now explore in more detail the conceptual changes leading from the lower anchor to the Grade 2 stepping stone.

From the Lower Anchor to the Grade 2 Stepping Stone

The reconceptualization that transforms the lower anchor into the Grade 2 stepping stone consists of a large number of intertwined changes in beliefs through which concepts are progressively modified in interaction with each other. Young children's sense of substantiality acts as a bridge between objects and nonsolids: some properties are extended from solids to liquids (e.g., weight) and others from liquids to solids (e.g., "made of" little pieces of material). Progressively constructing a collection of properties shared by solid objects and liquid samples is the process that underlies viewing solid objects as chunks of solid material (foregrounding "kind of stuff" while backgrounding shape, size, and function) and samples of nonsolids as objects (foregrounding size, weight, and being countable). In other words, it is the process by which the object construal and the material construal become relevant to both solid objects and nonsolid samples. Starting to explore liquefying and solidifying familiar materials (e.g., water, chocolate, wax) is another bridge between objects and nonsolid samples, as are aggregates (e.g., sand) which can be poured and fall to the bottom of containers, like liquids, but are made of small pieces of solid materials. Unlike the lower anchor, the Grade 2 stepping stone contains the superordinate concept of material and the concept amount of material. These concepts are elaborated further below.

The Grade 2 stepping stone also includes a sense of "occupying a certain amount of space." Children build on their belief that two objects cannot occupy the same location at the same time, and on their emerging concepts of amount of material and of solids and liquids as an ontological category, to qualitatively relate

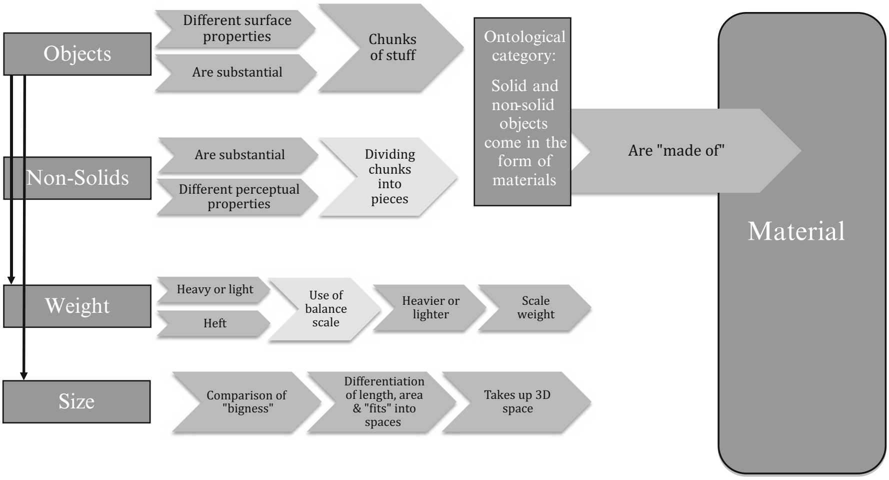


Fig. 3 Examples of interdependent conceptual changes

the bigness of objects to the amount of aggregate or liquid they displace (burying a large object produces a bigger pile of sand than burying a small object). This is the first step toward a quantified concept of occupied 3-D space. Concurrently, students learn to measure and differentiate length and area (see, e.g., Lehrer 2003). They also learn that scales are more reliable then heft for comparing weights. This allows discovering liquids have weight and that the weight of objects depends on what material they are made of. Inherent in the K-2 reconceptualization is a move from interpretations based on perceptual properties to interpretations based on more abstract concepts anchored in quantification. This is consistent with a progressive epistemology shift—from believing that the unaided senses tell the truth to placing more trust in measuring quantities with instruments. Figure 3 illustrates examples of the interdependent nature of the conceptual changes that occur throughout the K-2 reconceptualization, which we will elaborate on in the following sections.

Translating LPM into a Curriculum: Lever Concepts for Grades K to 2

The previous sections have highlighted that the reconceptualization captured by LPM consists of a large number of new beliefs and changes in existing beliefs; they also emphasize how intertwined those belief changes are. Translating LPM into a curriculum therefore requires prioritizing conceptual changes carefully: Which one should we start with so others can follow? Which one is most likely, at a given point, to move the knowledge network forward rather than create confusion or misunderstandings?

We use the theoretical construct *lever concept* to choose which core concepts to focus on in each grade range. Lever concepts for a grade range are the core concepts that already have a rich content at the beginning of that grade range and are relatively closer to the form targeted by instruction than other core concepts. Thus they provide multiple points of contact with instructional material, can be revised relatively quickly, and can participate in the revisions of other core concepts. Being a lever is a temporary status certain core concepts take in certain grade bands. Lever concepts in a grade range are core concepts that play a key role in the curriculum and students' learning in that grade range; in other words, core concepts come in and out of being lever concepts, as the knowledge network gets restructured, richer, and more complex. For example, weight, material, and amount of material become lever concepts in the third grade; by then, they are rich, explicit, and sufficiently articulated to be the topics of systematic investigations designed to move them and their interrelations further toward scientific understanding and contribute to the construction of other concepts (e.g., volume). In the K-2 range, *object*, *nonsolid*, *and size* (*bigness*) are the lever concepts. Once revised, they contribute to the construction of the concepts material and amount of material.

Supporting the Material Construal in the K-2 Learning Progression

As we have shown, young children's knowledge about material is far from compatible with a scientific concept. Many kindergartners lack a concept of material as distinct from object, and particularly as what objects *are made of*. One reason is that the object construal has been prominent since infancy; adopting the material construal requires viewing an object as two different things, something young children find difficult (Flavell 1986). Additionally, caregivers, who also construe solids predominantly as objects, tend to label objects rather than materials and to attribute material properties to object ("Don't drop that glass, it will break").

However, several aspects of preschoolers' knowledge of objects can contribute to the development of the concept of solid material. Most of them know at least a few material names, although they may not produce them when prompted. Some have also started to make inferences about material properties. In a study with 4-year-olds (from privileged backgrounds), children were given pairs of unfamiliar objects made of unfamiliar materials to heft and were also told "This one is a dax" ("Dax" is a nonsense word). They were then shown the same two shapes but made of the opposite material and asked either "Which is heavier?" or "Which is a dax?" They performed significantly above chance on both tasks (Wiser et al. 2008), showing that they were starting to understand that weight[4] is associated with material properties such as color and texture, rather than shape.

[4]The objects in each trial were matched for size.

This early intuitive knowledge can be built on in several ways. Becoming familiar with the names and properties of a larger number of materials as well as the superordinate “material” and the locution “made of” should contribute to developing the material construal of objects. Perceptual properties can be the basis on which to start. Once the concept of material has gained some traction, one can introduce properties that are not directly perceived (e.g., melting point) and progressively have students discover that they are in fact more reliable than some perceptual properties in identifying materials.

Introducing “made of” is especially important because it highlights the distinction and relation between object and material, but it is not sufficient. The meaning of “made of” must come from elsewhere—exploring physical transformations (cutting and grinding) should be helpful. Cutting solid chunks into smaller pieces, starting with materials that keep most of their perceptual properties when transformed (e.g., plaster), will help children to progressively strengthen the relation between objects and the materials of which they are made.

If our intuition is correct, and preschoolers’ knowledge about nonsolids includes important characteristics of the scientific concept of material, building up the similarities between liquid and solid samples should also help students develop a material construal of objects. This is learning by analogy (e.g., Gentner 2003; Fauconnier 1997): making similarities between solids and liquids salient (e.g., having weight and amount) should help students “import” properties of liquids, most importantly the material construal, into the domain of solid objects, as well as develop the superordinate concept of material applying to both.

Supporting the Concept of Amount of Material in the K-2 Learning Progression

As mentioned, we prefer a domain-specific account of children’s performance on Piaget’s amount conservation tasks and think of those tasks as about the concept itself rather than its conservation. To compare the ball and the pancake in terms of amount of clay, one needs to think of them as “chunks of clay,” i.e., one needs to apply the material construal to them. But for young children, clay is not yet a material in the sense of being what the ball is *made of* and therefore “more” does not mean “greater amount of material” because *amount of material* is not yet in place. Thus, when they are asked “Does the ball have the same amount of clay as the pancake?” their responses are not in reference to amount. Rather, what is salient is that the ball becomes a different *object*. Children answer “No,” meaning “the ball and the pancake are not the same.” Somewhat older children may correctly say “Yes, it is the same clay.” We surmise these children have a more advanced concept of material but no concept of amount. Finally, even saying “it is not more clay because you did not add any” is not evidence for a concept of amount either because, early in development, “more” refers to an action—“adding” or “doing again” (e.g., “more tickling”). This makes the task itself problematic, whether it is about conservation or about amount itself.

This exegesis of the Piagetian task leads us to conclude that focusing on conservation takes attention away from the very construction of the concept of amount. Sophian's (2000) and our own amount studies indirectly support our hypothesis that the development of the concept of amount is based on a compositional model of material[5] (Wiser et al., 2011). Once one has a compositional model of material, one can quantify amount and conservation "comes almost for free." If a chunk of material is conceptualized as a set of equal-sized pieces of that material, it follows that reshaping it merely rearranges the pieces while maintaining their number, and does not alter their amount. In other words, conservation is a by-product of having a concept of amount. This account of amount conservation is similar to one given by Piaget himself, who notes that it is the bridge between object permanence in infancy and the conservation of different continuous quantities in early and middle childhood (Piaget and Inhelder 1974). However, this is not one to which he returns, giving prominence instead to conceptual development being a consequence of the development of logical abilities.

This explanation implies that to have a concept of amount, one must have a concept of number and know that individual pieces do not appear or disappear. The latter is known from infancy. Number however should not be taken for granted. Although kindergartners know how to count, they do not all understand the cardinal meaning of number—that the last count word represents the number of items in a set. Cardinality is inherent in all measurements: in "This ribbon is 6 inches long," "six" refers to the whole set of six 1-in. long segments aligned along the ribbon. Therefore children's numerical development and the development of measurement are part and parcel of LPM, and quantifying amount of material and constructing a concept of material are intertwined developments.

Kindergarten Training Study

In this pilot study, we focused on the core concepts material (in particular, the material construal of objects) and amount of material and targeted a few of the early conceptual changes in the K-2 learning progression. Our goal was to test whether an intervention based on LPM would lead children to revise their concepts.

Intervention for Experimental Group

This intervention study embodies our view of reconceptualization as a progressive reorganization of a network of beliefs: each curricular unit focuses on the relations among several concepts and aims at small changes in those relations toward scientific understanding.

---

[5] Piaget recognizes the importance of composition and decomposition in the development of matter but his main account of amount conservation is in terms of logical abilities, that is, the account that dominates the literature.

Material Construal Activities

The main goal of these activities was to foster the material construal of objects via hands-on explorations of specific objects and materials and emphasis on linguistic constructions. Children explored, described, categorized, and labeled objects of different shape, size, and material. They were encouraged to use contrasting grammatical constructions ("This cylinder is not pointy" vs. "Plaster is soft") and to notice the equivalence of others ("This is a wood cylinder" and "This cylinder is made of wood"). They contrasted values taken by object and material properties ("Is cement a rough or smooth material?" and "Is this sphere large, medium, or small?"). These activities aimed to provide the superordinate labels that make the difference between object and material construals explicit, scaffold how to organize information relevant to object vs. material when a new object is encountered, and help children develop and strengthen new relations among concepts.

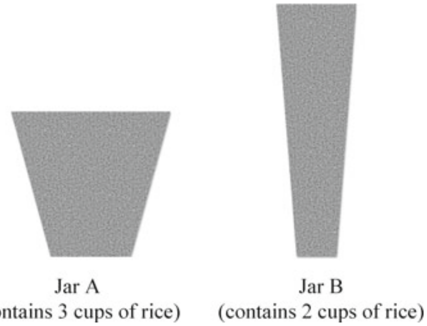
Sorting by material and shape "families." Children were presented an array of objects in various materials–wood, concrete, Styrofoam, wax, and sponge–in various shapes: cubes, spheres, triangular prisms, and cylinders. The facilitator initiated a discussion about ways the objects were similar or different. While synthesizing children's responses, she introduced the terms "material" and "made of." The following discussions focused on learning the names of the shapes and materials. Children then sorted the objects into "families" by placing them on different colored mats according to shape and then according to material.

How smart is your hand? The objects were displayed in front of the children; the duplicate of one of the objects was placed into an opaque bag while children kept their eyes closed. A volunteer felt inside the bag to determine which of the objects was inside. Children were encouraged to explicitly identify properties and attribute them to objects or to materials. For example, they were asked what material the object could be made of, and how they knew (typical responses included "I think it is sponge because it is squishy" or "I think it is Styrofoam because it makes a noise when I scratch it"). The facilitator reinforced the identification of such properties as a means of choosing one material over another. Similar emphasis was placed on shape as children identified objects.

Amount of Material Activities

These activities were based on our hypothesis that the concept *amount [of material]* would have little meaning at first and that the compositional model is central to constructing it. Again, we relied on hands-on experiences and specific linguistic input to help children give meaning to "amount of." We scaffolded the compositional model by having children build and take apart Lego constructions. In Lego constructions, the blocks (units) are visible within the whole and thus provide visible embodiments of "[the construction] is *composed of* (identical) blocks." The concept of amount and the compositional model were further explored using jars of rice. Both Lego and rice activities highlighted that amounts are measured and compared

Fig. 4 Example of jars of rice used in experimental condition



using 3D units and implicitly demonstrated that linear dimensions are not necessarily relevant when amounts are compared.

Lego Towers. The facilitator presented two identical three-block Lego towers and asked children if one tower had more plastic or if both towers had the same amount of plastic (most children agreed the towers had the same amount of plastic). She then reconstructed one tower into a new shape and asked again about amount of plastic (many children responded that the taller tower now had more). After counting that there were still three blocks in each, most children agreed that they had the same amount of plastic. The constructions were then placed on the scale. This activity was repeated with larger numbers of Legos. Placing the constructions on the scale was introduced as "another way to tell whether it is the same amount of plastic."[6]

Jars of Rice. Children were presented two jars of rice of different shape and asked which jar had more rice; they chose Jar B. (See Fig. 4.) Then they poured the

[6]The generalizations we are targeting are of course not correct in all contexts. For example, they assumed that our objects did not have hidden holes (e.g., hollow cube), that all the Lego blocks were the same except in color, that there were not two materials that looked identical but were in fact different, etc. … It is our strong belief that all generalizations have limitations; but they can be very useful pedagogically and pragmatically. We have argued elsewhere that "All matter has weight," one of the central tenets of the Grade 5 stepping stone, is essential to progressing toward "All matter has mass" (Wiser et al. 2012; Foster and Wiser 2012). Karmiloff-Smith's (1974) "If you want to get ahead, get a theory" captures our position. Qualifying statements too early and making them more scientifically "accurate" are detrimental pedagogical moves. Stepping stones are "imperfect" but powerful knowledge. In the present study, the overgeneralization "same number of equal pieces made of the same material = same weight = same amount of material" is a productive step, conceptually. Children who develop a concept of material will be able, later, to coordinate it with size and shape in more sophisticated ways. Without this first generalization, they may not develop the concept material at all. The same point applies to several material properties—e.g., "bends easily" come to mind. "Bends easily" depends not only on material but on the shape of the object and its width (so is breakability and transparency). But it is a property that children easily associate with material and it is a conceptually powerful (in fact essential) starting point. Once they "do their job" of helping construct the idea that some properties are maintained across shape change and cutting into large pieces, other properties can be introduced which characterize materials more reliably. Once foam is known by those other characteristics, it will be easy to learn "foam objects are bendable only when they are thin enough." This in turn is because, by then, foam, bendable, and thin will have meanings that make the sentence interpretable and informative.

rice into measuring cups and back into jars to discover that Jar A actually filled more cups. The facilitator again used the balance scale to show that Jar A outweighed Jar B.

The Conceptual Role of Weight

Weight was backgrounded but not ignored: we used a balance scale to support quantitatively amount comparisons and an ordinal weight line in the Material Construal activities. By aligning objects along a weight line first according to heft and then scale comparisons, children were establishing a qualitative association between weight and size and between weight and material, while discovering scales are more precise and objective than hefting. No formal relation was emphasized: children were invited to formulate that if one looks at all the objects made of the same material, bigger ones are heavier than smaller ones, and if one looks at all the objects of the same size, weight depends on material. This is the first step in developing quantitative relations among weight, volume, and kind of material, which also enriches and strengthens the concept of material identity (weight is characteristic of material when size is controlled).

Ordinal weight line. Children were asked to arrange six objects by weight (wood, wax, and sponge cubes in two sizes). This was first done by hefting (with a bit of difficulty and discrepancy). The facilitator then presented the balance scale as a way "to know for sure"; children used the scale and placed the object along a weight line accordingly. In discussion, the facilitator highlighted two patterns: (1) when objects are the same size, the wood object is heavier than the wax object and the wax object is heavier than the sponge object, and (2) when objects are the same material, big ones are heavier than small ones. Afterward, children were able to respond to questions about why the heavy ones are heavy with statements like "There is more stuff (or more wax, etc.) in the heavy ones", and "Soft things are lighter and hard things are heavier." Of course we did not intend to teach density but rather to provide a first association between material and weight and between size and weight as a stepping stone to it.

Method

Participants. Participants were recruited from elementary schools in Worcester, Massachusetts, in which 60 % of students are eligible for free or reduced lunch and represent diverse ethnic backgrounds. In total, 33 kindergartners were recruited: 20 in the Experimental group and 13 in the Control group.

Procedure. The intervention consisted of six 20–30-min sessions over the course of 2 weeks; the first three sessions focused on material, while the last three

Fig. 5 Material trial: "This one bends easily"

Fig. 6 Function trial: "This one holds a light switch"

focused on amount quantification. Sessions with the Control group consisted of class discussions of artworks, including about materials as it related to the artworks and hands-on activities such as making a mosaic.

Pre- and Posttests

To evaluate our training, we conducted pre- and posttests on material, amount, and number.

Material construal task. This task tested whether children could appropriately adopt the material construal of objects. The pretest had 12 trials: 8 material trials interspersed with 2 name trials and 2 function trials. For each of the material trials, the child was presented with a pair of objects (A and B). The child was told that object A was "squishy" or "magnetic," for example, and that object B was not. Children experimented with the objects to verify those statements. The child was then presented with a second pair of objects which he/she was not allowed to handle: the first was the same material as A and the same shape as B, and the second was the same material as B and the same shape as A (see Fig. 5). The experimenter asked, "Which is [squishy, magnetic, etc.]?" In the name and function trials, the child was presented with one novel object. The experimenter said "This is used for [holding light switches]" or "This is called a [dax]." The child was then presented with three new objects: one of the same material as the first but a different shape, one of the same shape as the first but a different material, and a distracter (see Fig. 6). The experimenter asked, "Which one is used for [holding light switches]?"

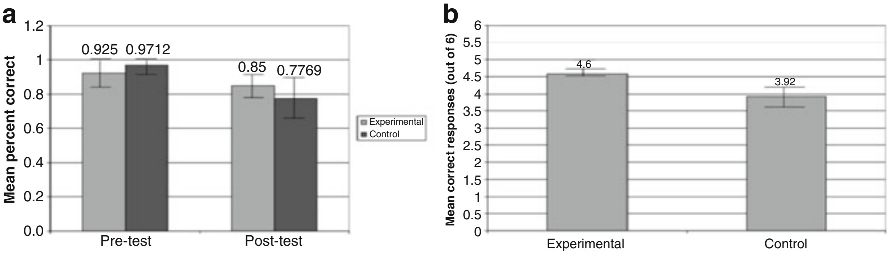


Fig. 7 (**a**) Repeated material properties—Experimental and control groups. (**b**) Novel posttest items—Experimental and control groups

The posttest was conducted in the same manner. It included four of the pretest material sets, three new sets with familiar material properties but more difficult stimuli (e.g., both objects in the pairs were the same color), three sets of entirely new materials and properties (e.g., gets cold fast when placed in ice water), and the same two function and two name items from the pretest.

Conservation of continuous quantities. One task was Piaget's clay-ball task. The experimenter stated that two balls had the same amount of clay and then squished one ball into a pancake and asked whether the pancake had more clay, less clay, or the same amount of clay as the ball. In the second task, one ball was broken into three pieces. The other ball and the pieces were placed on two plates and the child was asked "Does one plate have more clay or do the two plates have the same amount of clay?" The task was repeated with six pieces. In the third task ("three-jar task"), equal quantities of water were poured into two identical jars, one cupful at a time as the experimenter counted aloud. Then, the water from one jar was poured into a third, taller and thinner jar. Before and after the transformation, the experimenter asked whether one jar has more water or if they each had the same amount.

Conservation of discrete quantities: *Piaget's number conservation task*. The experimenter prepared a row of 12 buttons then handed the child a bag of buttons and asked, "Can you make a row that is exactly like mine?" The experimenter then asked whether the child's row contained the same number of buttons, more buttons, or less buttons as the experimenter's. The first row of buttons was then spread out and the question was repeated.

Results

Material

The results are presented in Fig. 7a and b. There was a significant improvement on the Material Construal Task (on the items that were used in both pre- and posttest) for the Experimental group, [t (19) = −3.56, $p < .01$]. The Control group showed no difference in performance from pre- to posttest.

The Experimental group also performed significantly better than the Control group on the novel items [$t(31) = 2.513$, $p = .017$]. Not surprisingly, overall performance was lower on these more difficult items.

Amount Conservation

Students in the Experimental group demonstrated significant improvement on the clay-piece task, as assessed by sign tests (of the 5 children who failed the pretest, all 5 passed the posttest, $p < .05$) and on the 3-jar task (of the 7 children who failed the pretest, all 7 passed the posttest, $p < .01$); improvement on the clay-pancake task did not quite reach significance—likely due to small sample size (of the 9 children who failed the pretest, 7 passed the posttest, $p = .07$). As hypothesized, the Control condition showed no improvement on any of the amount conservation tasks ($p > .25$ for all tasks).

Number

Children in the Experimental groups also improved significantly on the number conservation task (of the 6 children who failed the pretest, all 6 passed the posttest, $p < .05$), with no such improvement in Control condition ($p = .25$).

Discussion

This pilot study indicates that a teaching intervention based on LPM can improve young children's amount conservation and their ability to apply the material construal to solid objects in a very short period of time (2 weeks). Children's progress on the Material task is consistent with their developing a material construal of objects.

Children's progress on both the clay tasks and the three-jar task is consistent with our hypothesis that decomposing and recomposing whole samples physically may help children develop a compositional model of material, which they could then apply to continuous samples. One Experimental group participant's posttest response in the clay pieces task, "I know they are the same because there are three pieces in the ball too," provides particularly striking evidence for this claim.

Our participants' progress, in conjunction with the lack of progress in earlier studies on conservation training based on reversibility and coordination of dimensions (Inhelder et al. 1974), supports our account of conservation over Piaget's. Rather than teaching coordination of linear dimensions, our training activities were about measuring and foregrounded that amount is about *number* of *3D* units. Conservation was highlighted only in the Lego activities. We tentatively conclude that, rather than learning that amount is conserved, children were integrating conservation into their emerging concept of amount. However, further work will be necessary to establish that the compositional model is indeed the mediator in developing the concept of amount, and that amount conservation is part and parcel of constructing the concept of amount, rather than a principle that is discovered separately.

Whether training on material interacted with training on amount cannot be assessed in this study. It is an empirical issue that can be explored by varying the order of learning activities. Whether our sequence of quantification activities, from Lego blocks to jars of rice, is optimal is also an empirical question. On the one hand, counting Lego blocks is a direct way to measure amounts of plastic, whereas counting cups of rice may not translate immediately into measuring amounts of rice (because one could construe the activity as counting cups, not rice amounts). On the other hand, we do not know if our participants' concept of solid material was sufficiently revised to support quantification of amount of solid material. In any case, a more elaborate curriculum on quantifying amount would start by comparing perceptually different quantities in order to capitalize on children's sense of bigness, rather than with transformations, and would be preceded by systematic explorations of nonsolid as well as solid materials.

The role of number in amount quantification may be somewhat similar to the role of weight in that establishing a relation between them while they both are only partially understood may contribute to progress on both. Measuring might contribute to the development of cardinality: understanding "there are 4 cups of rice in this jar" as "the amount of rice in this jar is 4 cups" implies that "four" refers to the set of four cups; it is not just the last count word said when pointing to each cup in turn. It is possible that, as children learn to quantify amount of material, the concept of amount and the concept of number mutually support each other's development. The only support for this hypothesis we have for the moment is that the kindergartners in our Experimental group improved their performance on number conservation despite the fact that they were given no training in cardinality. We will need to include a more stringent test of cardinality in the future to assess the merit of our hypothesis. Finally the scope of this study was too limited to assess the role of language in fostering conceptual change. Future studies will include language comprehension and language production measures.

Overall Conclusions

We presented the above training study to illustrate a learning progression approach to teaching about matter. In a full K-2 curriculum, students would explore a range of aggregates and liquids, as well as solid materials. They would learn new names and new intensive properties relevant to material classification. Links would be made between categorizing solid and nonsolid materials. Starting with obviously different quantities of nonsolids, students could measure them by counting the number of measuring containers they fill and correlate sample sizes with numbers of amount units. This would establish a bridge between their intuitive quantification of nonsolids in terms of bigness (big pile of sand, small bottle of milk) and their quantification of solid objects (counting) and pave the way to quantifying amounts of solid samples. Using a scale, they would discover that liquids indeed have weight, and that it is related to amount. These explorations would contribute to the revision of the weight concept, the development of the amount concept, and the relation between the two. These conceptual changes would also be part of the development of two ontological categories: *material* and *solids and liquids*, a precursor of *matter*. Students would learn that all (macroscopic) samples of all materials have weight, that they can be thought of as made of a certain number of 3D units, and that their amount does not change when they are reshaped or divided. This would contribute to coalesce solid and nonsolid materials into a single category as well as broaden the range of application of the material construal to include solid objects.

A full K-2 curriculum would also include units that allow inquiry into whether material identity changes when one cuts and grinds solid samples, the properties of materials that stay constant during those transformations, including non-perceptual ones, and the link between material properties and function. Addressing this issue would strengthen the differentiation and integration of the object and material construals of objects. The curriculum would also include inquiries that would build a qualitative sense of volume. Note that, in LPM, bigness is a precursor of both amount and volume. To become amount, it needs to be quantified and become a characteristic of the material the object is made rather than the object itself; to become volume, it also needs to be quantified and become a characteristic of the space occupied by the object rather than the object itself.

Although the Grade 2 stepping stone is quite far from a scientific conceptualization of matter, it is conceptually closer to it than the lower anchor. After being strengthened and enriched, the category solids and liquids will undergo two major conceptual changes in later elementary grades. One will lead to the belief that pieces of solids or liquids too small to be visible have weight and occupy space. The second will be that gases are material in the same sense as solids and liquids. This is very close to a scientific understanding of matter except for the concept of mass, which will be developed in middle school, based on amount of material and volume. These conceptual changes, and others that take place in the Grade 3–5 range, illustrate the conceptual role of the Grade 2 stepping stone in making them possible. For example, conservation of material identity across phase change becomes graspable because students can already apply the material construal to a sample that turns from solid to liquid, materials are identified by properties that are no longer all perceptual, and materials have been explicitly differentiated from state (during grinding). These understandings would not have been possible without the prior ability to apply the material construal to both solids and liquids.

These various considerations illustrate how complex the reconceptualization of matter is—it involves a large number of small but coordinated steps and many kinds of conceptual changes: coalescences, differentiations, generalizations, more stringent specifications, breaking some old links among concepts and percepts, and creating new ones. Moreover, these changes are heavily interdependent. Such reconceptualization is inevitably slow. LPM is a long road to reconceptualization paved with "approximations." It requires the support of curricula with a long time span that gives ample time to revisit relations between concepts many times, in broader and broader contexts, and in relation to more sophisticated epistemological knowledge.

The training study also serves to illustrate the iterative processes involved in taking a learning progression approach to science teaching and the revisable nature of learning progressions. It shows we might be on the right track: our participants learned what we hypothesized, providing empirical evidence for the early part of LPM. However future studies may show that providing different key experiences or targeting conceptual changes in a different order may be more beneficial, leading us to revise LPM before we start designing a full K-2 curriculum. Testing K-2 curricular units based on LPM may also help to reexamine the learning progression and curriculum for Grades 3–5 we developed as part of the INQUIRY project. (See http://inquiryproject.terc.edu/.) The study's success within a population of lower socioeconomic status should help to motivate research aiming to close the socioeconomic gap in early math and science aptitude. The INQUIRY project's implementation of an LPM-based curriculum for Grades 3–5 saw similar (and broader-based) success in urban schools, although with no middle-class comparison. We suggest that the results of our training study, paired with the success of INQUIRY, add to a growing body of literature that suggests learning progressions can act as "equalizers"—contributing to efforts to close the income gap in science education (Corcoran et al. 2009).

Our intervention shows that kindergartners have the capacity to start building core concepts about matter. One reason to start teaching those core concepts in kindergarten is how complex and how slow the processes underlying reconceptualization are. Starting early allows taking small, meaningful steps; revisiting core concepts in several contexts and in combination with several other concepts; and progressively developing models and other representational tools which contribute to the reconceptualization. The sooner one implements LPM-based curricula, the sooner students can start developing solid conceptual foundations and continue building on those foundations, avoiding some of the "dead ends" they encounter and misconceptions they develop in the contexts of traditional curricula. A K-12 learning progression for matter would insure that coherence and consistency among learning experiences within and across grade is maintained throughout schooling.

Acknowledgments The authors thank the Mosakowski Institute for Public Enterprise at Clark University for the financial support for some of this research. In addition, we gratefully acknowledge Theresa E. Jackson for her perspective and contributions to this work. Thanks also go to the two anonymous reviewers for suggestions that improved the manuscript.

References

Baillargeon, R. (2002). The acquisition of physical knowledge in infancy: A summary in eight lessons. In U. Goswami (Ed.), *Blackwell handbook of childhood cognitive development*. London: Blackwell Publishers.

Bertenthal, B. I., & Clifton, R. K. (1998). Perception and action. In W. Damon (Ed.), *Handbook of child psychology* (Vol. 2, pp. 51–102). Hoboken: Wiley.

Bloom, P. (2000). *How children learn the meaning of words*. Cambridge, MA: MIT Press.

Bower, T. (1989). The perceptual world of the newborn child. In A. Slater & G. Bremner (Eds.), *Infant development* (pp. 85–98). Hillsdate: Lawrence Erlbaum Associates.

Casey, A. (2011). *Young children's concept of amount of stuff in two different contexts*. Unpublished undergraduate honors thesis, Clark University, Worcester.

Corcoran, T., Mosher, F., & Rogat, A. (2009). *Learning progressions in science: An evidence-based approach to reform*. Philadelphia: Consortium for Policy Research in Education.

Delgado, C., & Krajcik, J. S. (2010). Developing a hypothetical multi-dimensional learning progression for the nature of matter. *Journal of Research in Science Teaching, 47*, 687–715.

Dickinson, D. K. (1987). The development of material kind. *Science Education, 71*, 615–628.

Fauconnier, G. (1997). *Mappings in thought and language*. Cambridge: Cambridge University Press.

Flavell, J. (1986). The development of children's knowledge about the appearance-reality distinction. *The American Psychologist, 41*, 418–425.

Foster, J., & Wiser, M. (2012). The potential of learning progression research on the development of science standards. In A. Alonzo & A. Gotwals (Eds.), *Learning progressions in science* (pp. 435–460). Rotterdam: Sense Publishers.

Gentner, D. (2003). Why we're so smart. In D. Gentner & S. Goldin-Meadow (Eds.), *Language in mind: Advances in the study of language and thought* (pp. 195–235). Cambridge, MA: MIT Press.

Hall, G. (1996). Naming solids and non solids: Children's default construals. *Cognitive Development, 11*, 229–264.

Huntley-Fenner, G., Carey, S., & Solimando, A. (2002). Objects are individuals but stuff doesn't count: Perceived rigidity and cohesiveness influence infants' representations of small groups of discrete entities. *Cognition, 85*, 203–211.

Inhelder, B., Sinclair, H., & Bovet, M. (1974). *Learning and the development of cognition*. Cambridge, MA: Harvard University Press.

Johnson, P. (1998). Progression in children's understanding of a basic particle theory: A longitudinal study. *International Journal of Science Education, 20*, 393–412.

Johnson, P. M. (2005). The development of children's concept of a substance: A longitudinal study of interaction between curriculum and learning. *Research in Science Education, 35*, 41–61.

Karmiloff-Smith, A. (1974). If you want to get ahead, get a theory. *Cognition, 3*, 195–212.

Krnel, D., Watson, R., & Glazar, S. A. (1998). Survey of research related to the development of the concept of "matter". *International Journal of Science Education, 20*, 257–289.

Lee, O., Eichinger, D. C., Anderson, C. W., Berkheimer, G. D., & Blakeslee, T. D. (1993). Changing middle school students' conceptions of matter and molecules. *Journal of Research in Science Teaching, 30*, 249–270.

Lehrer, R. (2003). Developing understanding of measurement. In J. Kilpatrick, W. G. Martin, & D. E. Schifter (Eds.), *A research companion to principles and standards for school mathematics* (pp. 179–192). Reston: National Council of Teachers of Mathematics.

Lehrer, R., Jacobson, C., Kemeny, V., & Strom, D. (1999). Building on children's intuitions to develop children's understanding of space. In E. Fennema & T. A. Romberg (Eds.), *Mathematics classrooms that promote understanding* (pp. 63–87). Mahwah: Lawrence Erlbaum.

Liu, X., & McKeough, A. (2005). Developmental growth in students' concept of energy: Analysis of selected items from the TIMSS database. *Journal of Research in Science Teaching, 42*, 493–517.

Metz, K. (1993). Preschoolers' developing knowledge of the pan-balance: New representation to transformed problem solving. *Cognition and Instruction, 11*(1), 31–93.

Mohan, L., Chen, J., & Anderson, C. W. (2009). Developing a multi-year learning progression for carbon cycling in socio-ecological systems. *Journal of Research in Science Teaching, 46*, 675–698.

Piaget, J., & Inhelder, B. (1974). *The child's construction of quantities: Conservation and atomism*. London: Routledge & Kegan Paul.

Pradas, M. (2010). *Young children's non verbal representations of* "*more*"*: Number and amount*. Unpublished undergraduate honors thesis, Clark University, Worcester.

Sarama, J., & Clements, D. H. (2009). *Early childhood mathematics education research. Learning trajectories for young children*. New York: Routledge.

Smith, C. L. (2007). Bootstrapping processes in the development of students' commonsense matter theories: Using analogical mappings, thought experiments, and learning to measure to promote conceptual restructuring. *Cognition and Instruction, 25*, 337–398.

Smith, C., Carey, S., & Wiser, M. (1985). On differentiation: A case study of the development of the concepts of size, weight and density. *Cognition, 21*, 177–237.

Smith, C., Maclin, D., Grosslight, L., & Davis, H. (1997). Teaching for understanding: A comparison of two approaches to teaching students about matter and density. *Cognition and Instruction, 15*, 317–393.

Smith, C. L., Solomon, G. E. A., & Carey, S. (2005). Never getting to zero: Elementary school students' understanding of the infinite divisibility of number and matter. *Cognitive Psychology, 51*, 101–120.

Smith, C. L., Wiser, M., Anderson, C. W., & Krajcik, J. (2006). Implications of research on children's learning for standards and assessment: A proposed learning progression for matter and atomic-molecular theory. *Measurement: Interdisciplinary Research and Perspectives, 14*, 1–98.

Smith, C., Wiser, M., & Carraher, D. (2010, March). *Using a comparative, longitudinal study with upper elementary school students to test some assumptions of a learning progression for matter*. Paper presented at the 83rd Annual National Association for Research in Science Teaching conference, Philadelphia.

Sophian, C. (2000). From numbers to quantities: Developments in preschool children's judgments about aggregate amount. *Developmental Psychology, 36*, 724–736.

Spelke, E. (1991). Physical knowledge in infancy: Reflections on Piaget's theory. In S. Carey & R. Gelman (Eds.), *The epigenesis of mind* (pp. 257–291). Hillsdale: Erlbaum.

Spelke, E. S. (2000). Core knowledge. *The American Psychologist, 55*, 1233–1243.

Stevens, S., Delgado, C., & Krajcik, J. (2010). Developing a hypothetical multi-dimensional learning progression for the nature of matter. *Journal of Research in Science Teaching, 45*, 687–715.

Stevens, S.Y., Shin, N., & Kracjik, J. (2009, June). *Toward a model for the development of an empirically tested learning progression*. Paper presented at the Learning Progressions in Science (LeaPS) Conference, Iowa City, IA.

Wiser, M., & Smith, C. L. (2008). Learning and teaching about matter in grades K-8: When should the atomic-molecular theory be introduced? In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 205–239). Hillsdale: Erlbaum.

Wiser, M., & Smith, C. L. (2009, August). *How does cognitive development inform the choice of core ideas in the physical sciences*? Commissioned paper presented at the National Research Council Conference on Core Ideas in Science, Washington, DC.

Wiser, M., Citrin, K., Drosos, A., & Hosek, S. (2008, June). *Young children's understanding of the relation between weight and material kind*. Poster presented at the 38thAnnual Meeting of the Jean Piaget Society, Quebec City.

Wiser, M., Casey, A., & Pradas, M. (2011). *The development of number and amount of material*. Presented at the 41st Annual Meeting of the Jean Piaget Society, Berkeley, California.

Wiser, M., Smith, C. L., & Doubler, S. (2012). Learning progressions as tools for curriculum development: Lessons from the inquiry project. In A. Alonzo & A. Gotwals (Eds.), *Learning progressions in science* (pp. 359–404). Rotterdam: Sense Publishers.

Part II
Students' and Teachers' Mental Models of the Particulate Nature of Matter

Understanding of Basic Particle Nature of Matter Concepts by Secondary School Students Following an Intervention Programme

David F. Treagust, A.L. Chandrasegaran, Lilia Halim, Eng-Tek Ong, Ahmad Nurulazam Md Zain, and Mageswary Karpudewan

Introduction

The study of science in general and chemistry in particular includes observing and explaining the behaviour of matter in its various forms. For students to be proficient in explaining the nature of matter, they have to possess a thorough understanding of the concepts about the particle theory of matter. In several educational systems, particle theory concepts are an important component of the primary and early high school (involving students aged 11–14 years) science curricula (Martin et al. 2004). Studies have been extensively conducted at various educational levels since the 1970s to evaluate the efficacy of instructional programmes to assess students' understandings of the key tenets of the kinetic particle theory of matter. These research findings have revealed poor understanding of the concepts among students, resulting in arguments

D.F. Treagust (✉)
Science and Mathematics Education Centre, Curtin University, Perth, Australia
e-mail: D.Treagust@curtin.edu.au

A.L. Chandrasegaran
Science and Mathematics Education Centre, Curtin University, Perth, Australia

L. Halim
Faculty of Education, National University of Malaysia, Bangi, Malaysia

E.-T. Ong
Faculty of Education and Human Development, Sultan Idris Education University, Tanjung Malim, Malaysia

A.N.M. Zain
National Higher Education Research Institute, University of Science Malaysia, George Town, Penang, Malaysia

M. Karpudewan
School of Educational Studies, University of Science Malaysia, George Town, Penang, Malaysia

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_6,

to delay the topic of particle theory of matter to later in the science curriculum (Harrison and Treagust 2002). Following on from the findings of previous studies (e.g. Johnstone 2007, 2010), the concern among science educators about when is the most appropriate time to introduce the concept of particles involving atoms and molecules in the science curriculum was also echoed by Tsaparlis et al. (2010). A report by these authors involving the introduction of a lower secondary chemistry course that is based on science education learning theories has suggested delaying the introduction of the concepts of atoms and molecules until such time when students are ready to assimilate these ideas in their cognitive structures (Tsaparlis et al. 2010).

A major obstacle to understanding particle concepts is students' intuitive belief that matter is continuous in nature rather than particulate, a view held by more than 50 % of students in a study from all levels of high school through to university (Nakhleh 1992). This finding is relevant to this study as the participants involved were in senior high school (grades 10 and 11) and of ages 16–17 years. Also, the belief that the particles in matter are in contact with each other with no empty spaces between the particles (Griffiths and Preston 1992; Nakhleh 1992; Lee et al. 1993) is ontologically different from the scientifically accepted view that the particles are discrete and dynamic and are separated from each other by empty space (de Vos and Verdonk 1996).

Another impediment is the belief that matter in a substance is continuous and yet consists of particles (Krnel et al. 1998). In a related study involving students aged 11–14 years, Johnson (1998) found that the majority of students held one of three models of matter, namely, (1) matter is a continuous substance, (2) matter consists of particles in a continuous substance, and (3) the particles with macroscopic properties are the substance. (See also the chapter "How Students' Understanding of Particle Theory Develops: A Learning Progression" by Johnson in this volume.) The notion that particles are in substances as opposed to the fact that substances are composed of particles is common among students. Lee et al. (1993) found this strongly held notion coupled with the belief of the presence of some kind of 'stuff' or air between the particles. The idea of particles floating in some kind of 'stuff' is reinforced by textbook diagrams depicting particles in a liquid with a line across the top (Andersson 1990; Harrison 2001).

Yet another belief is that the particles in a substance possess the macroscopic properties that are displayed by the substance (Andersson 1986; Ben-Zvi et al. 1986; Taber 1996; Johnson 1998). Studies involving formation of gases during changes of state have indicated that grades 4–7 students (aged 9–15 years) are unable to conceptualise a gas as being a substance, while students are generally of the opinion that a gas is weightless or is lighter than solids or liquids (Stavy 1988). Also, none of the grade 7 students and only 25 % of the grade 8 students have been found to be able to explain the changes in state with reference to the kinetic particle theory. It appears, therefore, that these younger students are only able to conceptualise a gas as a type of matter in macroscopic terms; only later on in their cognitive development are they able to conceptualise an abstract submicroscopic interpretation in terms of the particles involved. These intuitive ideas about the nature of matter that students have acquired in their early years of schooling appear to change to scientifically acceptable understandings only to a limited extent after instruction (Stavy 1988).

In a recent study using 11 multiple-choice items, although about 41–78 % of all 148 grades 9–10 students involved in the study indicated consistent understanding of the three conceptual categories that were investigated, very few revealed understanding of the related concepts when their explanations for making a particular choice were taken into account (Treagust et al. 2010).

In this study, grades 10 and 11 students' understanding of particle theory concepts was assessed using a diagnostic instrument (the *Particle Theory Diagnostic Instrument*, *PTDI*) after implementing an intervention instructional programme. Two-tier multiple-choice items like the ones in the *PTDI* require a content response to the first tier; the second tier of the multiple-choice items requires students to provide a justification for their choice of response in the first tier. These items have proven to be very useful as formative assessment tools as these are convenient to administer and easy to mark (Treagust 1988, 1995). Use of such items provides teachers with information about students' understanding of particular science concepts (Treagust and Chandrasegaran 2007), enabling them to take cognisance of students' alternative conceptions in their classroom instruction. A study of the research literature does not reveal the use of two-tier multiple-choice items to assess students' understanding of particle concepts; the studies have mainly used open-ended questions in their investigations.

This study involved assessing improvements in grades 10 and 11 students' understanding of particle theory concepts of matter after the implementation of an instructional programme that was developed in a previous study (Treagust et al. 2011). The improvements in understanding were assessed in three key conceptual categories, namely, (1) intermolecular spacing in matter (CC1), (2) the influence of intermolecular forces on changes of state (CC2), and (3) diffusion in liquids and gases (CC3), using the *PTDI* consisting of 11 two-tier multiple-choice items.

Context of the Study

After 6 years in primary (elementary) school, students in Malaysia spend 5 years in secondary school (grades 7–11, referred to as Forms 1–5). In the final 2 years (grades 10 and 11), about 30 % of students study pure sciences, i.e. science as three separate subjects (physics, chemistry, and biology) based on their performance in a national examination that is held at the end of Form 3 (third year of secondary schooling). Following this period of study, students who intend to proceed to university traditionally spend 2 years in Form 6 (postsecondary school). Over the past three decades special matriculation programmes have been introduced for admission to particular local and overseas universities, eliminating the need to complete the traditional Form 6 programme.

Particle theory concepts are first referred to in the Malaysian general science curriculum in grade 7 – the first year of secondary schooling. The relevant curriculum documents (Ministry of Education 2002) relating to the teaching and learning of particle concepts were examined to assist in deciding on the objectives of the study. The curriculum specifications relating to matter and its particle concepts are as follows:

Theme: Matter in Nature
Learning objective 2: Understanding the three states of matter.
Learning outcomes: A student is able to state the three states of matter, state the arrangement of particles in the three states of matter, and state the differences in the movement of particles in the three states of matter.

In grades 10 and 11, the curriculum specifications relating to particle concepts (Ministry of Education 2005) for students who study pure sciences are as follows:

Theme: Matter around us
Learning objective: Analysing matter
Learning outcomes: The students should be able to describe the nature of matter, define atoms, molecules and ions, state the kinetic theory of matter, relate the change in the state of matter to the change in heat [*sic*], relate the change in heat [*sic*] to the change in kinetic energy of particles and explain the interconversion of the states of matter in terms of the kinetic theory of matter.

In defining the scope of this study we decided to adopt what de Vos and Verdonk (1996) consider to be correct scientific ideas about the particulate nature of matter. These ideas that are summarised below are relevant to the concepts of (1) CC1, (2) CC2, and (3) CC3 relating to this study (see above).

1. All matter consists of entities called particles. Individual particles are too small to be seen. They behave as hard solid objects. In drawings, the particles may be represented as small circles or dots.
2. Motion is a permanent feature of all particles. There is a direct relation between the temperature of an amount of matter and the average kinetic energy of the particles.
3. In a gas, the empty space between particles is much larger than that occupied by the particles themselves. Particles of a gas in an enclosed space are randomly distributed.
4. There is mutual attraction between any two particles, but its magnitude decreases rapidly with distance. In a gas, the attraction is negligible, except at high pressure and low temperature.
5. In liquids and solids, the particles are much closer together and subject to mutual attraction. In solids, the particles may be arranged in regular patterns, with each particle being able only to vibrate around a fixed position. In liquids, the particles are irregularly arranged and move from place to place within a fixed volume.

(Adapted from de Vos and Verdonk 1996, p. 659)

Objectives of the Study and Research Questions

The main objective of this study was to assess understanding of particle concepts of matter among secondary school students in three conceptual categories, namely, (1) intermolecular spacing in matter, (2) the influence of intermolecular forces on changes of state, and (3) diffusion in liquids and gases. These concepts are first taught in Form 3 (the third year of secondary schooling). In order to assess these understandings among grades 10 and 11 students who were involved in this study, the following research questions were formulated:

1. Is there a significant difference in the understanding of particle theory of matter concepts as evidenced by the pretest and posttest scores among grades 10 and 11 students involved in the study?
2. How consistent are students from the four schools in their understanding of intermolecular spacing in matter?
3. How consistent are students from the four schools in their understanding of the influence of intermolecular forces on changes of state?
4. How consistent are students from the four schools in their understanding of diffusion in liquids and gases?

By 'consistent' in research questions 2–4, we mean the extent to which students provided correct responses to all the three or four related items in each of the three conceptual categories. If students possessed understanding of the concepts relating to conceptual category CC1 about the intermolecular spacing in matter, say, we would expect them to correctly answer all four items in that conceptual category.

Methodology

Design

The study involved evaluating an instructional strategy in a pretest–posttest design (Cohen et al. 2000) using quantitative data. The last four authors conducted the study in six classes from four secondary schools, while the first two authors monitored each stage of the study to ensure uniformity in implementation by providing them with a research protocol whose stages are summarised in Table 1.

The *PTDI* pretest data were analysed using the SPSS statistics software (version 18) to ascertain students' understanding of the related concepts prior to instruction. An intervention instructional programme (see Appendix) was next implemented. About a week after completing the intervention programme, the *PTDI* was administered again as a posttest and the data analysed to ascertain any improvements in students' understanding of particle concepts.

Research Samples

Six convenience samples (Merriam 1998) totalling 172 students in grades 10 and 11 from four secondary schools in Malaysia were involved. All students in the six classes were high-achieving students who had qualified to study the three separate

Table 1 Stages in the implementation of the research programme

Stages	Research activity
1	Administration of the *PTDI* as pretest
2	Analysis of pretest data to determine frequencies of alternative conceptions held by students using SPSS statistics software (version 18)
3	Identification of alternative conceptions held by students
4	Implementation of the intervention programme
5	Administration of the *PTDI* as posttest (not earlier than a week after completion of the intervention programme)
6	Analysis of pretest and posttest data involving frequencies, *t*-test, and ANOVA analyses using SPSS statistics software (version 18)

Table 2 Distribution of participants involved in the study

Sample	School label	School type	Grade levels	Number of participants
1	A	All boys	11	23
2	B	All girls	10	31
3	B	All girls	11	30
4	C	Co-educational	10	37
5	D	Co-educational	10	27
6	D	Co-educational	10	24
Total				172

sciences based on their performance in the Form 3 national examination mentioned previously. Details of the six samples are shown in Table 2.

Structure of the PTDI

The 11 two-tier multiple-choice items in the *PTDI* involving understanding of basic particle theory concepts were developed in a previous study (Treagust et al. 2011). The key concepts embodied in these 11 items were those adapted from de Vos and Verdonk (1996), referred to earlier.

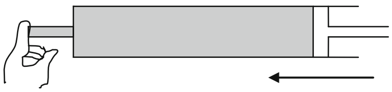
The 11 items were classified into the three conceptual categories labelled CC1, CC2, and CC3, with each category consisting 3–4 items as follows: (1) CC1 (intermolecular spacing in states of matter) involving Items 3, 4, 5, and 11; (2) CC2 (the influence of intermolecular forces on changes of state) involving Items 8, 9, and 10; and (3) CC3 (diffusion in liquids and gases) involving Items 1, 2, 6, and 7. An example of an item in each conceptual category is shown in Figs. 1, 2, and 3.

Intervention Instructional Programme

An intervention programme extending over eight lessons of about 45-min duration each was implemented based on a protocol that was prepared by the first two authors to ensure uniformity in implementation by the other four authors. The instructors

Item 4

The diagram shows a coloured gas being compressed in a gas syringe until the plunger could not be pushed any further. The experiment was repeated using the same volume of a coloured liquid.



It was found that the final volume of the gas was:

A Much less than that of the liquid.

B Much greater than that of the liquid.

The reason for my choice of answer is:

1 The particles in the gas are more widely spaced.

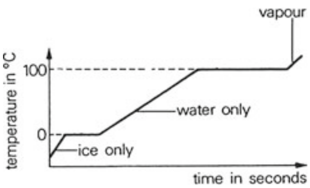
2 The particles in the gas move more freely.

3 The particles in the gas move randomly in all directions.

Fig. 1 Example of an item in the conceptual category ‘intermolecular spacing in states of matter’ (CC1)

Item 9

The diagram shows how the temperature changes when some ice at a temperature below 0ºC is heated to above 100ºC.



We may deduce that that liquid water can exist at its boiling point of 100ºC.

A True B False

The reason for my choice of answer is:

1 At the boiling point water molecules change immediately into steam.

2 The molecules are moving fast enough to change completely into steam.

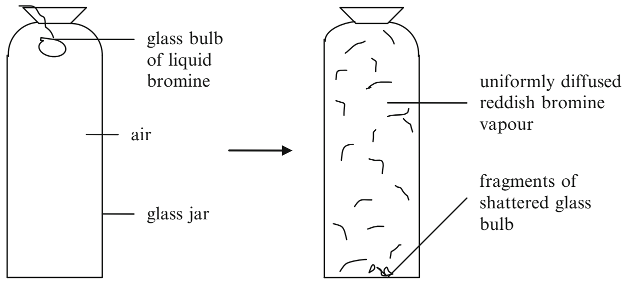
3 The attractive forces between all the water molecules have to be weakened.

Fig. 2 Example of an item in the conceptual category ‘influence of intermolecular forces on changes of state’ (CC2)

involved (teachers of the six classes) demonstrated, or the students performed, the experiments associated with each item of the *PTDI* where possible and followed up with discussions to explain students’ observations.

After each activity, students were required to discuss their observations in their own groups, following which the instructor solicited explanations from representative groups. The composition of the groups was left entirely to the discretion of the instructors involved. In the ensuing whole class discussion, the instructor facilitated the students in acquiring more scientifically acceptable understanding of the concept(s) involved, while at the same time addressing the previously identified alternative conceptions in the pretest. Details of the intervention instructional programme are provided in Appendix.

Item 2
A small glass bulb containing liquid bromine was dropped into a tall jar of air and the jar was immediately stoppered. The bulb shattered on hitting the bottom of the jar, releasing bromine vapour. After several hours, reddish bromine vapour had diffused uniformly throughout the jar. If the experiment is repeated after pumping out most of the air from the jar, we would expect the reddish bromine vapour to diffuse and fill the jar within a few seconds.



A True B False

The reason for my choice of answer is:
1 The particles in the gas are more widely spaced.
2 The particles in the gas move more freely.
3 The particles in the gas move randomly in all directions.

Fig. 3 Example of an item in the conceptual category ‘diffusion in liquids and gases’ (CC3)

Diagnostic Instrument (PTDI) Psychometrics

Students’ responses to the 11 items were analysed to determine the frequencies of correct responses using SPSS software (version 18). A response to an item in the *PTDI* was considered correct only if students responded correctly to both tiers of the item. These recoded responses (‘1’ for correct and ‘0’ for incorrect) to the 11 items in the posttest for the 172 respondents were used to compute the Cronbach’s alpha reliability coefficient, and was found to be 0.66. This value of the coefficient for the *PTDI* was greater than the threshold value of 0.5 proposed by Nunally and Bernstein (1994). All the items had been content-validated by four academics and two senior teachers before being used in a previous study (Treagust et al. 2011). Hence, it may be concluded that the 11 items in the *PTDI* were consistent in assessing understanding of particle concepts among the respondents in the study.

Results and Discussion

Analysis of Students’ Correct Responses to Items in the Pretest and Posttest of the PTDI

Students’ pretest and posttest responses to the first tier and the combined tiers to each of the 11 items were analysed, and the percentage of correct responses to the items are summarised in Table 3. There was reason for providing data for the first

Table 3 The percentage of students who correctly answered the first part and both parts of the items in the *PTDI* ($N = 172$)

	Percentage of students who provided correct responses			
	Pretest		Posttest	
Item no.	First part	Both parts	First part	Both parts
1	92.4	27.9	95.5	47.7
2	72.7	36.6	93.0	46.5
3	77.3	61.6	79.7	65.7
4	71.5	32.6	86.6	62.8
5	70.9	32.0	82.6	48.8
6	88.4	25.6	98.3	50.0
7	92.4	61.0	97.1	80.8
8	85.5	18.6	95.9	45.3
9	41.3	9.9	41.9	18.6
10	93.0	43.0	95.3	68.0
11	77.3	59.3	76.7	69.8
Mean	72.07	34.82	86.69	54.91

Table 4 Paired samples *t*-test results comparing pretest and posttest total scores ($N = 172$)

Pretest total scores		Posttest total scores				
Mean	SD	Mean	SD	*t*-value	*p*	Cohen's *d*
4.08	1.79	6.04	2.49	10.10	0.000	0.90

tier and the combined tiers of the items: the first tier of an item usually solicits a content response that a student could have merely memorised, while the second tier requires a reason for selecting a particular response in the first tier. So, correct responses to both tiers of an item reflect a respondents' knowledge with understanding of the concept involved.

In general, in this study the percentage of correct responses to the combined tier was lower than that for the first tier for all items in both the pretest and the posttest. For all items, except Item 11, there was an improvement in the posttest scores over the pretest scores, thus lending support to the overall efficacy of the intervention programme in facilitating understanding of the associated particle concepts.

Pretest–Posttest Comparisons of Total Scores in the PTDI

A paired samples *t*-test analysis was performed in order to further evaluate the efficacy of the intervention programme in assessing students' understanding of particle theory of matter concepts (see Table 4).

The results indicate that the efficacy of the intervention programme in facilitating understanding of particle concepts showed a statistically significant ($p < 0.001$) improvement in the posttest mean scores over the pretest mean scores. The strength of the difference between the pretest and posttest mean scores may be determined by computing the effect size, Cohen's *d*. Cohen (1988) has defined the effect size as

Table 5 Students' consistency in understanding of particle theory concepts ($N = 172$)

Conceptual categories	Items	Consistent understanding[a] – number of students (percentage)
CC1: intermolecular spacing	3, 4, 5, 11	53 (30.8)
CC2: influence of intermolecular forces on changes of state	8, 9, 10	12 (7.0)
CC3: diffusion in liquids and gases	1, 2, 6, 7	28 (16.3)

[a]Students provided correct responses to all items in the conceptual categories

being small when $d = 0.2$, medium when $d = 0.5$, and large when $d = 0.8$. The effect size value in Table 4 indicates that the mean total score difference was relatively large and educationally important in the posttest compared to that of the pretest.

A one-way repeated measures ANOVA was next conducted to compare the test scores in the pretest and the posttest, when there was a significant effect for the time when the two tests were administered [Wilks' Lambda = 0.63, $F(1,171) = 102.02$, $p < 0.0001$]. An additional one-way ANOVA was next conducted to explore the effect of grade level on the posttest scores. Although there was a difference in the mean scores of the grade 10 students ($N = 119$) and the grade 11 students ($N = 53$), the difference was not statistically significant at the $p < 0.05$ level [grade 10, $M = 6.28$, SD = 2.40; grade 11, $M = 5.51$, SD = 2.62; $F(1) = 3.55$, $p = 0.061$].

Analysis of Data in the Conceptual Categories

The posttest data were analysed in order to assess consistency in students' understanding of particle concepts in the three conceptual categories. The consistency in understanding of intermolecular spacing (conceptual category 1) was determined by analysing students' responses to find out the percentage of students who correctly answered all four Items 3, 4, 5, and 11. Similarly, for the influence of intermolecular forces on changes of state (conceptual category 2), consistency in their understanding was computed by determining the percentage of students who correctly answered all three Items 8, 9, and 10 and, for diffusion in liquids and gases (conceptual category 3), by determining the percentage of students who correctly answered all four Items 1, 2, 6, and 7. In general, students displayed very limited consistency in understanding of the associated concepts in all three conceptual categories as only a small percentage of students (ranging from 7 to 30.8 %) were able to provide correct responses to all the three or four items pertaining to each conceptual category (see Table 5).

Conclusion and Implications for Classroom Instruction

The findings of this study suggest that these grades 10 and 11 Malaysian students continue to display limited understanding of particle theory of matter concepts. This state of affairs seems to persist despite having been identified in studies over several decades, a probable indication of the slow process of the translation of research findings into classroom practice. In addition, the research findings are evident of the inherent difficulty in understanding the particle nature of matter concepts. Nevertheless, this study has shown that some measure of success can be achieved if appropriate instructional programmes are carefully planned and implemented in the classroom.

Several conclusions may be drawn from the findings of this study. With respect to research question 1 (Is there a significant difference in the understanding of particle theory of matter concepts as evidenced by the pretest and posttest scores among grades 10 and 11 students involved in the study?), the findings suggest that the intervention programme was successful in facilitating improved understanding of particle concepts of matter, as evidenced by the results of a paired samples *t*-test analysis on the mean pretest and posttest scores of the *PTDI*. There was a significant difference between the pretest scores ($M=4.08$, SD = 1.79) and the posttest scores [$M=6.04$, SD = 2.49; $t(171)=10.10$, $p=0.000$].

The posttest scores for all samples also indicated improvement in all but one item (see Table 3). The percentage of correct responses to the first tier of the items in the posttest ranged from 76.7 to 98.3 % for all except Item 9. However, the percentage of correct responses to the combined tiers in the posttest was lower, ranging from 18.6 to 80.8 %, suggesting that although there was improved understanding (compared to the pretest scores) of the relevant concepts, students may not have acquired sufficient understanding of these concepts.

The results obtained by analysing students' responses to items in the three conceptual categories indicated very limited consistency in understanding of the associated concepts. Research question 2 (How consistent are students from the four schools in their understanding of intermolecular spacing in matter?) was evaluated in Items 3, 4, 5, and 11. Only 30.8 % of the students answered all four items correctly to indicate understanding that the particles in liquids and gases were mobile (unlike the particles in solids), with the particles in gases being able to move freely and occupy all available space, while those in liquids moved about within a fixed volume (about the same as that occupied by the substance in the solid state).

There was very much less consistency in students' understanding with regard to research question 3 (How consistent are students from the four schools in their understanding of the influence of intermolecular forces on changes of state?) that was evaluated using students' responses to Items 8, 9, and 10. Only 7 % of students answered all three items correctly to indicate understanding that intermolecular forces had to be overcome in order to change a substance from the solid state to the liquid state and finally to the gaseous state.

Regarding research question 4 (How consistent are students from the four schools in their understanding of diffusion in liquids and gases?), students' consistency in understanding of diffusion in liquids and gases as a result of the random zigzag motion of particles in liquids and gases due to continuous collisions between particles was evaluated using Items 1, 2, 6, and 7. Only 16.3 % of the students answered all the four items correctly.

The findings of this study have also raised several relevant implications for classroom instruction. As particle theory of matter concepts are essential for understanding of other topics and concepts in chemistry that are introduced later on in the curriculum, for example, the mole, stoichiometry, and reaction kinetics, it is important that students acquire a strong understanding of these particle theory concepts early on in their science studies.

First, the curriculum specifications need to be provided in greater detail, clearly explaining the major particle theory of matter concepts in a systematic and structured manner, similar to the way in which they were presented earlier in this chapter (de Vos and Verdonk 1996). Second, the findings suggest that grades 10 and 11 students do not have a coherent understanding of particle theory of matter concepts that were investigated in this study. It is therefore advantageous that these important concepts are regularly revisited from earlier school years in order to reinforce students' understanding of particle concepts of matter. Third, it is important that teachers are familiar with the manner in which students' understanding about particle concepts of matter are developed. As suggested by Stavy (1988), for example, when students first encounter gases in grade 7, they have a tendency to describe a gas in terms of its macroscopic properties. Only in subsequent years do they understand a gas as a state of matter and finally are able to conceptualise the particulate nature of matter.

Fourth, teachers need to use a variety of instructional strategies in order to expose students to a range of experiences in different contexts so that they are able to acquire a more coherent and consistent view of particle theory concepts of matter. In this respect students should be provided with opportunities to perform relevant experiments or observe demonstrations (e.g. in Harrison and Treagust 2002) and to discuss in groups the reasons for the observed changes in matter in terms of the particles that are involved (Johnson 2006). Other instructional strategies include the use of models, simulations, and analogies (Coll et al. 2005; Harrison and Treagust 2000; Justi and Gilbert 2002). In addition several video clips can be freely downloaded from the Internet, with the dramatic and almost instantaneous diffusion of bromine in partial vacuum as an example. Also, for concepts that were difficult for the students to comprehend, the teachers could challenge students' conceptions using instructional strategies like discrepant events, the predict–observe–explain strategy, Socratic questioning techniques, and small group discussions, to mention a few, in order to engender more acceptable understandings of scientific concepts.

Finally, although the implications are not exhaustive, the use of frequent and ongoing assessment in the form of embedded assessment by teachers has the potential to facilitate improved understanding of the concepts relating to the particle theory of matter by students (Treagust et al. 2003).

In conclusion, the instructional protocol that was used in the intervention instructional programme in this study has proven to some extent to be very effective in bringing about the desired improvements in students' understanding of particle concepts.

Appendix: Intervention Instructional Programme on Kinetic Particle Theory

Lesson 1: Administration of the *Particle Theory Diagnostic Instrument, PTDI* (pretest)

Lesson 2: Diffusion in liquids and gases (related to Items 1 and 2 of the *PTDI*)

Objectives of the lesson

To facilitate understanding of the following concepts related to the two items:

Item 1: Randomly moving air particles constantly collide with the larger smoke particles causing the smoke particles to move in a random zigzag manner.

Item 2: Fewer collisions occur between bromine and air molecules in a partially evacuated container, causing the bromine to diffuse almost instantaneously.

Lesson sequence

1. Working in groups, students observe, under a microscope, the movement of smoke particles in a smoke cell. Alternatively, project the smoke cell on a screen using an overhead projector.
2. Engage students preferably in group discussions with appropriate questions (including Socratic questions) leading to understanding of what has occurred. Solicit responses from several group representatives.
3. Demonstrate bromine diffusion using the YouTube video clip found on the Internet. URL: www.youtube.com/watch?v=ZAGloLXO9L0
4. Again, engage students preferably in group discussions with appropriate questions leading to understanding of what has occurred. Solicit responses from different group representatives.

Lesson 3: Diffusion in liquids and gases (cont.) (related to Items 6 and 7 of the *PTDI*)

Objectives of the lesson

To facilitate understanding of the following concepts related to the two items:

Item 6: It takes a long time for red dye particles to diffuse uniformly throughout water because the particles are constantly colliding with each other and with the randomly moving water molecules.

Item 7: Some rapidly moving molecules in an inflated balloon gain sufficient energy during collisions to enable them to pass through the pores in the balloon skin causing the balloon to slowly deflate.

Lesson sequence

1. (At the end of the previous lesson, carefully place some red or other coloured food dye, using a pipette, below some water in several test tubes and allow to stand for the next lesson.)

During the lesson, students examine the test tubes in groups; the water would be coloured uniformly red throughout.

Engage students in group discussions to explain why the water has become uniformly coloured red. Solicit responses from several group representatives.

2. (At the end of the previous lesson, tie up 5 or 6 inflated balloons and leave aside.)

During the lesson, students examine the balloons (which have deflated) in their groups.

Engage students in group discussions to explain why the balloons have become deflated. Pose suitable questions for students to discuss.

Lesson 4: Intermolecular spacing in matter (related to Items 3 and 4 of the *PTDI*)

Objectives of the lesson

To facilitate understanding of the following concepts related to the two items:

Item 3: A liquid is able to flow and take up the shape of the container it is poured into, without a change in its volume because the particles in a liquid slide and slip past each other within a fixed volume due to the weaker attractions than when in the solid state.

(continued)

Appendix (continued)

Item 4: When a gas is compressed, the particles are pushed closer together resulting in a much smaller volume because the spacing between particles in a gas is much greater than in a liquid. The particles in a liquid cannot be pushed any closer together, so there is no change in volume.

Lesson sequence

1. Students perform simple activity (in groups) of carefully transferring a fixed amount of water from one container to another of different shape and confirming the volume each time, avoiding spillage in the process.
2. Engage students in group discussions to explain why the volume of the water is approximately constant (making allowance for some 'wetting' of the glass container). Pose suitable questions for students to discuss. Solicit responses from several group representatives.
3. Working in groups, students compress a fixed volume of air in a gas syringe; then repeat the activity with an equal volume of a coloured liquid (or water).
4. Engage students in group discussions to explain why the volume of the water is unchanged while that of the air decreases on compressing. Pose suitable questions for students to discuss. Solicit responses from different group representatives.

Lesson 5: Intermolecular spacing in matter (related to Items 5 and 11 of the *PTDI*)

Objectives of the lesson

To facilitate understanding of the following concepts related to the two items:

Item 5: When a gas is compressed, the widely spaced particles are pushed much closer together, resulting in a decrease in its volume without a change in the mass of the gas.

Item 11: When the two liquids are mixed, some of the molecules occupy the spaces between the molecules of the two liquids resulting in a slight decrease in the total volume.

Lesson sequence

1. Students perform simple activity (in groups) involving compressing a fixed volume of air in a gas syringe.
2. Engage students in group discussions to explain why the volume of the air decreases on compressing while its mass remains unchanged. Pose suitable questions for students to discuss.

Solicit responses from several group representatives.

3. Students are provided with two 50-cm^3 measuring cylinders, one containing fine sand filled to the 25-cm^3 mark and the other filled with green peas to the 25-cm^3 mark. Working in groups, students pour the sand into the measuring cylinder of green peas and gently tap the cylinder until a steady final volume is observed. Discussing in groups, students explain why the total volume is less than 50 cm^3. Pose suitable questions to enable students to transfer their understanding to the example of mixing known volumes of alcohol and water. Solicit responses from different group representatives

Lesson 6: Influence of intermolecular forces on changes of state of matter (related to Item 8 of the *PTDI*)

Objectives of the lesson

To facilitate understanding of the following concepts related to the item:

Item 8: At the boiling point of water, the heat energy that is supplied does not raise the temperature of the water while it is boiling; instead it is used to weaken the attractive forces between molecules and pull them apart from neighbouring molecules until all the molecules have changed into the gaseous state.

Lesson sequence

1. Students perform in groups the heating of naphthalene in a boiling tube suspended in a water bath, recording the temperature every minute or so until just all the solid has melted. Students then plot a heating curve.

(continued)

Appendix (continued)

2. Engage students in group discussions to explain the way the shape of the graph changes as the solid is heated. Draw a similar graph on the board and pose suitable questions for students to discuss.

Solicit responses from several group representatives.

Lesson 7: Influence of intermolecular forces on changes of state of matter (cont.) (related to Items 9 and 10 of the *PTDI*)

Objectives of the lesson

To facilitate understanding of the following concepts related to the two items:

Item 9: When water begins to boil, both liquid water and steam are present until all the water molecules have gained sufficient energy to break away from their neighbouring molecules.

Item 10: When a solid melts or when a liquid boils, heat energy is absorbed in order to weaken the attractive forces between the molecules and pull the molecules further apart from each other.

Lesson sequence

1. Draw a heating curve on the board to show how the temperature changes as ice is heated from about – 10 °C to just above its boiling point. Explain that just as in Item 8, the temperature of water remains constant until it changes into steam.
2. Engage students to discuss in groups to explain why water can exist at its boiling point. Pose suitable questions for students to discuss. Solicit responses from several group representatives.
3. Illustrate using molecular models of H_2O to show how the van der Waals bonds are weakened as ice is heated until it boils (ignore the hydrogen bonding in water). Then illustrate the reverse process as steam condenses to water and then water freezes to ice.

Pose relevant questions to students. Questions are best directed to the groups to first discuss before soliciting their responses.

Lesson 8: Administration of *Particle Theory Diagnostic Instrument* (posttest) about a week after completing the intervention programme.

References

Andersson, B. (1986). Pupils' explanations of some aspects of chemical reactions. *Science Education, 70*, 549–563.

Andersson, B. (1990). Pupil's conceptions of matter and its transformations (age 12–16). *Studies in Science Education, 18*, 53–85.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education, 63*, 64–66.

Cohen, J. (1988). *Statistical power analysis for the behavioural sciences* (2nd ed.). Hillsdale: Lawrence Erlbaum.

Cohen, L., Manion, L., & Morrison, K. (2000). *Research methods in education* (5th ed.). London: Routledge Falmer.

Coll, R. K., France, B., & Taylor, I. (2005). The role of models and analogies in science. *International Journal of Science Education, 27*(2), 183–198.

de Vos, W., & Verdonk, A. H. (1996). The particulate nature of matter in science education and in science. *Journal of Research in Science Teaching, 33*, 557–664.

Griffiths, A. K., & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*, 611–628.

Harrison, A. G. (2001). Textbooks for outcomes science: A review. *The Queensland Science Teacher, 27*(6), 20–22.

Harrison, A. G., & Treagust, D. F. (2000). A typology of school science models. *International Journal of Science Education, 22*(9), 1011–1026.

Harrison, A. G., & Treagust, D. F. (2002). The particulate nature of matter: Challenges in understanding the submicroscopic world. In J. K. Gilbert, O. De Jong, R. Justi, D. F. Treagust, & J.H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 189–212). Dordrecht: Kluwer.

Johnson, P. (1998). Progression in children's understanding of 'basic' particle theory: A longitudinal study. *International journal of Science Education, 20*(4), 393–412.

Johnson, P. (2006). The development of students' understanding of the particle theory and its role in their conception of macroscopic phenomena. In H. Fischler & C. S. Reiners (Eds.), *Die Teilchenstructur der Materie im Physik- und Chemieunterricht (The particle structure of materials in physics and chemistry instruction)* (pp. 109–143). Berlin: Logos.

Johnstone, A. H. (2007). Science education: We know the answers, let's look at the problems. *Proceedings of the 5th Greek Conference on science education and new technologies in education* (Issue A), 1–13. Ioannina: Greece. Available at: http://www.kodipheet.gr/fifth_conf/pdf_synedriou/teyxos_A/1_kentrikes_omilies/1_KO-4-Johnstone.pdf)

Johnstone, A. H. (2010). You can't get there from here. *Journal of Chemical Education, 87*, 22–27.

Justi, R., & Gilbert, J. K. (2002). Models and modelling in chemical education. In J. K. Gilbert, O. de Jong, R. Justi, D. F. Treagust, & J. H. van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 189–212). Dordrecht: Kluwer.

Krnel, D., Watson, R., & Glazar, S. A. (1998). Survey of research related to the development of the concept of 'matter'. *International Journal of Science Education, 20*, 257–389.

Lee, O., Eichinger, D. C., Anderson, C. W., Berkheimer, G. D., & Blakeslee, T. D. (1993). Changing middle school students' conceptions of matter and molecules. *Journal of Research in Science Teaching, 30*, 249–270.

Martin, O., Mullis, I., Gonzales, E., & Chrostowski, S. (2004). *TIMSS 2003 international science report*. International Association for the Evaluation of Educational Achievement (IEA). Chestnut Hill: TIMMS and PIRLS International Study Centre, Boston College.

Merriam, S. B. (1998). *Qualitative research and case study application in education*. San Francisco: Jossey-Bass.

Ministry of Education. (2002). *Curriculum specifications-science form 1*. Retrieved October 28, 2010, from www.moe.gov.my/bpk/sp_hsp/sains/kbsm/hsp_sc_f1.pdf

Ministry of Education. (2005). *Curriculum specifications-chemistry form 4*. Retrieved October 28, 2010, from www.moe.gov.my/bpk/sp_hsp/sains/kbsm/hsp_chemistry_f4.pdf

Nakhleh, M. B. (1992). Why some students don't learn chemistry: Chemical misconceptions. *Journal of Chemical Education, 69*, 191–196.

Nunally, J. C., & Bernstein, I. H. (1994). *Psychometric theory* (3rd ed.). New York: McGraw-Hill.

Stavy, R. (1988). Children's conception of gas. *International Journal of Science Education, 10*, 553–560.

Taber, K. S. (1996). Chlorine as an oxide, heat causes molecules to melt, and sodium reacts badly in chlorine: a survey of the background knowledge of one A-level chemistry class. *School Science Review, 78*(282), 39–48.

Treagust, D. F. (1988). The development and use of diagnostic instruments to evaluate students' misconceptions in science. *International Journal of Science Education, 10*, 159–169.

Treagust, D. F. (1995). Diagnostic assessment of students' science concepts. In S. Glynn & R. Duit (Eds.), *Learning science in the schools: Research reforming practice* (pp. 327–346). Mahwah: Lawrence Erlbaum.

Treagust, D. F., & Chandrasegaran, A. L. (2007). The Taiwan national science concept learning study in an international perspective. *International Journal of Science Education, 29*, 391–403.

Treagust, D. F., Chandrasegaran, A. L., Crowley, J., Yung, B. H. W., Cheong, I. P.-A., & Othman, J. (2010). Evaluating understanding of kinetic particle theory concepts relating to states of matter, changes of state and diffusion: A cross-national study. *International Journal of Science and Mathematics Education, 8*(1), 141–164.

Treagust, D. F., Chandrasegaran, A. L., Zain, A. N. M., Karpudewan, M., Ong, E. T., & Halim, L. (2011). Evaluation of an intervention instructional program to facilitate understanding of basic particle concepts among students enrolled in several levels of study [Diagnostic Assessment special issue]. *Chemistry Education Research and Practice, 12*(2), 251–261.

Treagust, D. F., Jacobowitz, R., Gallagher, J. J., & Parker, J. (2003). Embedded assessment in your teaching. *Science Scope, 26*(6), 36–39.

Tsaparlis, G., Kolioulis, D., & Pappa, E. (2010). Lower-secondary introductory chemistry course: A novel approach based on science-education theories, with emphasis on the macroscopic approach, and the delayed meaningful teaching of the concepts of molecule and atom. *Chemistry Education Research and Practice, 11*, 107–117.

The Use of Multiple Perspectives of Conceptual Change to Investigate Students' Mental Models of Gas Particles

Mei-Hung Chiu and Shiao-Lan Chung

Introduction

This chapter addresses the difficulties students commonly experience when conceptualizing the behavior of gas particles. Specifically, this study examined and compared students' mental models, regarding diffusion of gas particles, both prior to and following model-based instruction. Research in students' conceptions has come to the consensus that learners come to school with some preconceptions of science that either facilitate or hinder their understanding of scientific phenomena. No matter the correctness, consistency, coherence, or completeness of a learner's conceptual understanding in science, students tend to rely on prior experiences and/or internal representations when interacting with instructional materials. In addition, science content becomes more abstract and complex and more inherently difficult to master, with each grade level. Thus, it is imperative that educators build an accurate scientific foundation upon which more advanced science learning is dependent. The next section reviews the research completed in the area of the nature of particles, in particular, gas particles and how gas particles function.

M.-H. Chiu (✉)
Graduate Institute of Science Education, National Taiwan Normal University, Taipei, Taiwan
e-mail: mhchiu@ntnu.edu.tw; meihungchiu@gmail.com

S.-L. Chung
Graduate Institute of Science Education, National Taiwan Normal University, Taipei, Taiwan

New Taipei Municipal New Taipei Senior High School, Taipei, Taiwan

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_7,

Nature of Gas Particles

What Do Students Know About the Nature of Particles?

There is considerable research investigating students' as well as teachers' conceptions of the structure and behavior of matter (e.g., Ben-Zvi et al. 1986; Chiu 2007a; Griffiths and Preston 1992; Harrison and Treagust 2002; Liang et al. 2011; Nakhleh et al. 2005; Nussbaum and Novick 1982; Smith et al. 2006). For instance, the pioneer work on gas particles conducted by Nussbaum and Novick (1982) showed that students tend to consider gases as fluid with a continuous nature instead of a particulate nature. Nakhleh et al. (2005) found that middle school students, while in possession of microlevel ideas, still showed significant misconceptions about matter. Similarly, Johnson and Papageorgiou (2010) found that ninth grade students thought that particles are the matter with macroscopic character. Chiu (2007a), in a large-scale study with about 7,000 junior high (grades 7–9) and 3,000 senior high (grades 10–12) students, found that around 20 % of the students believed hydrogen particles distribute in the upper portion of a container, while oxygen particles sink to the bottom of the container because of their differing weights. Liang et al. (2011) found similar results when most of their eighth and ninth grade students reported that molecular weight is a main factor influencing distribution of gas particles. Although heavier gases do sink to the bottom while lighter gases flow above in large spaces, this does not apply to a small container in which the gases would be normally distributed. Across studies, students lacked the concept of randomization and then mistook the attribution of molecular weight in explaining diffusion in a small container.

From several longitudinal studies, consistent findings highlight the importance of time in conceptual change of learning particle theory. For instance, in a 3-year longitudinal study, Johnson (1998) categorized two successive dimensions of science understanding with regard to learning particle theory: (1) continuous particulate and (2) macroscopic collective. He reported that students appeared to gradually progress through one dimension at a time. Although the basic particle theory was taught from the start and revisited in each unit, many students still lagged behind in their understanding of the main points of particulate and collective perspectives that science instruction aims for. The findings suggest that students' thinking develops in one dimension at a time rather than both dimensions simultaneously.

Margel et al. (2008) also conducted a longitudinal study with about 1,000 junior high school students (grades 7–9) examining the students' conceptions of the particulate nature of matter (PNM). Over a period of 3 years, the students were asked to describe in words and drawings the structure of multiple materials. In students' written responses, they found four types of explanations, namely: (1) daily macroscopic explanations (based on common knowledge), (2) scientific explanations (using scientific terms learned in class), (3) particulate explanations (describing the basic particulate model, regarding all materials as substances consisting of particles, without distinguishing between the types of particles), and (4) molecular explanations (elaboration of the particulate model and the distinction between different types of particles). In a series of five tests over the 3 years of the study, 75 % of the students adhered to a macroscopic conceptual model at Test 1; however, 85 % of the students provided a microscopic description, and 36 % of these students provided a molecular description at Test 4. Eighty-three percent of the students still held to the microscopic conception at Test 5. The researchers claimed that an effective instructional approach must consist of multiple pathways for improving student understanding of the nature of matter.

Adadan et al. (2010) investigated nineteen eleventh graders' conceptual pathways following multi-representational instruction on the PNM over a 3-month period of instruction. They found the students' patterns of conceptual pathways of the PNM went from no change to radical progress after instruction. In between the stable state with no change to radical change, they also found some additional pathways with certain features, namely, radical progress and either stable or a slight decay of full scientific understanding of the PNM, or from alternative fragments or alternative with scientific fragments to a full scientific understanding of the PNM. Of course, they also found no or slight progression from pre- to post-instruction. Although the majority of students (13 out of 19) maintained their radical progress in their conceptual understandings of the PNM, there were some students who regressed to fragments or alternative conceptions. The positive impact of long-term instruction and multiple representations might open an avenue for improving students' understanding of the microscopic world.

Franco and Taber (2009) claim that research has repeatedly demonstrated successful outcomes in student achievement in developing PNM over a minimum period of time as discussed above. However, they found that most students in their study (a 3-year intervention) were not able to use the particle model to provide explanations to match scientific reasoning in English secondary schools. This inconsistent finding revealed the role of culture and context in learning that results in different contexts in different countries regarding teaching the concept of particles.

Tsitsipis et al. (2009) used a stepwise multiple regression analysis to investigate what factors influenced students' understanding of the structure of matter and its changes of state. They found that there were three significant cognitive variables that influenced students' understanding: (1) logical thinking, (2) cognitive style (field dependent or independent), and (3) convergent/divergent thinking. Among them, logical thinking was the most dominant variable in predicting the students' achievement. Their findings provided evidence to support the idea that formal reasoning plays an important role in understanding scientific phenomena as proposed by Lawson (1985).

Several studies have shown that teacher professional development is needed to improve teachers' understanding of the nature of matter in order to present the concepts correctly and meaningfully. For instance, Papageorgiou et al. (2010) found that primary school teachers shared similar misunderstandings as their students regarding physical phenomena such as continuous matter around particles. However, the teachers exhibited greater resistance in accepting ideas associated with particles in the solid state than the gas state, while the students had more difficulty with particles in the gas state. Liang et al. (2011) found that teachers underestimated students' performance because they lacked experience in accessing students' reasoning arguments and then overestimated students' performance after instruction.

As discussed above, it is evident that students tend to develop their internal representations of matter in a manner inconsistent with scientifically accepted models. Not only does science content need to be scaffolded to increase understanding of the microscopic view of particles, but teachers should also be made aware of how and why the basic concepts of the PNM become a challenge for school learners who often construct faulty scientific models. There is an emerging need to improve teachers' awareness of students' difficulties and to develop effective models for successful science teaching and learning.

Possible Explanations for Conceptual Changes

Traditionally, researchers attributed difficulty in learning scientific concepts to the complexity and abstraction of the concepts to be learned. However, there are different theories or explanations from cognitive psychology, psychology, and computational science that provide insightful frameworks for interpreting students' alternative conceptions. In this chapter, we explore how these theories contribute to our understanding of students' learning about gas particles.

We agree that changes in students' mental representations, from naive and intuitive to scientific understanding, are not easily achieved due to the abstraction and complexity of the concepts and time duration of instruction. However, we also believe that the characteristics of complexity and abstraction are not the sole causes for the difficulty in learning the concepts of structure and behavior of particulate matter. Alternative explanations should be taken into account to widen our understanding of the difficulties associated with learning the microscopic view of particles. In the following sections, we use the *Research And InstructioN-Based/Oriented Work* (RAINBOW) approach to guide the discussion. Specifically, we use Chi's ontological categories of concepts approach to investigate students' performance in the area of gas particles. We also bring perspectives from complex system domains to extend the theoretical background that could provide some insightful interpretations for learning the PNM and about gas behaviors in particular.

Integrative Approach

Many researchers have developed theories to explain the patterns, characteristics, structures, relations, and products of learners' internal representations of a scientific phenomenon. Researchers use multidimensional approaches to interpret students' conceptual change in learning science (Duit and Treagust 2003; Treagust and Duit 2008; Tyson et al. 1997). Drawing on an analysis of the existing literature, Chiu

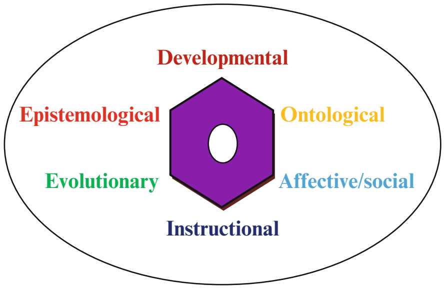


Fig. 1 Components of the RAINBOW approach (reprinted with permission from Nova Publishers)

took these approaches one step further and proposed a comprehensive framework that integrates current research with a conceptual change model and further provides a multiple perspectives approach—Research And InstructioN-Based/Oriented Work (RAINBOW)—to conceptual change in science learning (Chiu 2007b; Chiu and Lin 2008). The components and related studies of the RAINBOW model are briefly depicted in Fig. 1.

The RAINBOW framework for conceptual change is based on cognitive psychology, developmental research, science education research, cognitive science, and educational research. Six perspectives were identified: (1) developmental (e.g., Toulmins 1972), (2) ontological (e.g., Chi 2005, 2008; Chi et al. 1994), (3) epistemological (e.g., Vosniadou 1994), (4) affective (e.g., Pintrich et al. 1993; Sinatra and Pintrich 2003; Sinatra and Mason 2008), (5) evolutionary (Lin and Chiu 2007), and (6) instructional (e.g., modeling approach, Chiu and Chung 2009). Figure 1 takes the structure of benzene as an analogy of the hybrid relations among the perspectives included in the RAINBOW approach. Each perspective contributes to uncovering students' nature of knowing, learning about science, and registering of knowledge into internal presentations to facilitate understanding. Five perspectives (the evolutionary perspective is excluded because of the complexity of the analysis involved) are considered in the following discussion. Specific emphasis on ontological and epistemological perspectives will be the goal for the remainder of this chapter.

Ontological Perspectives

In Chi and her colleagues' series of work (1992, 1994, 1997; 2005; 2008), they claim that there are three types of ontological categories that concepts are assigned to: Entity, Process, and Mental state. (Her terms have changed over time. Here we follow Chi's definitions from 2005.) Conceptual change is the process of shifting conceptions across ontological boundaries (such as from Entity to Process). The reassignment process, such as from Entity to Process is considered an ontological shift requiring radical conceptual change. The Process category has two ontologically distinct kinds of scientific processes, "direct" and "emergent." Take the circulatory system and diffusion as examples. The former is considered a direct category because it is caused by the heart pumping blood through the body. The diffusion mechanism is considered an emergent process because it is caused by a collection of distinct particles' behaviors. In short, "a *direct* process is one that usually has an identifiable agent that causes some outcome in a sequential and dependent sort of way" (Chi 2008, p. 74), while "the *emergent* processes have neither an identifiable causal agent or agents nor an identifiable sequence of stages" (Chi 2008, p. 75). If a student's misconceptions stem from *direct* kinds of processes (such as flow of blood in human circulation), then they belong to the same ontological element as the correct conception. Therefore, this type of misconception might not be as robust as initially believed. If a student's conceptions of *Emergent* processes (such as diffusion of dye in water) are mistaken as *Direct* processes, they are robust to correct because they need to be reassigned to a different ontological element (Chi 2005).

In this study, we explore Chi's theory on students' conceptions of gas particle behavior and investigate whether there are big jumps between ontological elements or transitional states that bridge elements. Therefore, we not only examined how students' conceptions changed as they moved from one ontological category to another but also investigated any changes in subcategories.

The causal mechanisms underlying these two kinds of processes possess a number of similarities (Chi 2005). The similarities are as follows: (1) both have global patterns (such as flow in circulation and diffusion) and components, (2) both can be discussed at multiple levels (such as aggregate or constituent level), (3) the components of both processes interact (such as the heart interacts with blood by pumping it), (4) both processes may be invisible (e.g., it is nearly impossible to see the constituent components for diffusion), (5) both involve numerous simple and complicated descriptors (such as color of blood, concentration, or equilibrium) about both the pattern and the components, and (6) both have various factors (conditions or variables) that can influence both the global patterns of flow and the local specific behavior of the components. However, the similarities cannot in principle be the source of differential learning via these two processes.

Apart from the similarities, there are fundamental differences between these two processes. From the mechanism perspective, there are three ways to discuss these differences, namely: (1) the behaviors of the components, (2) the treatment of the components as either classes or collection, and (3) the causal mechanism relating the components and the patterns. Ten exclusive attributes of two of these differences are listed in Table 1 (see Chi 2008, pp. 174–180).

In sum, these two processes allow students to construct a mental model of the phenomenon. The nature of the aggregate components or their constituents is directly causing the global pattern which is referred to as *direct*. In contrast, for an *emergent* process, neither the aggregate components themselves nor their constituents are directly (or indirectly) causing the global pattern to occur. It is the collective interaction of all the constituent components that cause the global pattern (Chi 2005). Because they share similar characteristics as discussed above, it is common for students to mistake the characteristics of *direct* processes with characteristics that actually belong to *emergent* processes. Even with instruction, this type of

Table 1 Ontological attributes of direct and emergent processes

	Direct processes	Emergent processes
Component level interactions	1. Distinct	Uniform
	2. Constrained	Unconstrained (random)
	3. Sequential	Simultaneous
	4. Dependent	Independent
	5. Terminating	Continuous
	6. Subgroup (or classes)	All components (or a collection of components)
Component-pattern relations	7. Direct	Nondirect
	8. Corresponding	Disjoint
	9. Differential status	Equivalent status
	10. Global goal or intentional	Local goal or unintentional

misconception is difficult to remediate. For instruction to be effective, it must target the misconception at the level at which it was formed. As such, we aim to identify the components that comprise students' mental models of gas behavior and the underlying mechanism of conceptual change following model-based instruction.

Epistemological Perspective

Apart from Chi's ontological approach, Vosniadou's (1994) epistemological approach took students' presupposition of knowledge as the framework to describe how epistemological and ontological presuppositions influence one's mental models in understanding knowledge in specific domains (such as mathematics and physics, Ioannides and Vosniadou 2002; Vosniadou and Verschaffel 2004). Vosniadou (1994) stated that presuppositions of the framework theory are based on everyday experience, confirmed over years, and then used to form a relatively coherent system of explanation. The process of conceptual change appears to involve a gradual lifting of the presuppositions of the framework theory and then the formation of more sophisticated models until conceptual change has been achieved (Vosniadou et al. 2008).

However, this view of consistent mental models of physical phenomena advocated by Vosniadou is inconsistent with the view proposed by diSessa who considers the conceptual system to be made up of fragmented phenomenological primitives (p-prims) that are generated from learners' daily life experiences. The debate between Vosniadou (Vosniadou et al. 2008) and diSessa (diSessa et al. 2004) on the consistency or fragments of mental models (which is not the emphasis of this article) continues. Nobes et al. (2005) agreed with diSessa et al. The majority of children in their study showed no evidence of possessing consistent models with internal consistency.

Complex Systems

Boccara (2010) identified the three common characteristics of complex systems: (1) they consist of a large number of interacting agents; (2) they exhibit emergence, that is, a self-organizing collective behavior difficult to anticipate from the knowledge of the agents' behavior; and (3) their emergent behavior does not result from the existence of a central controller.

In complex systems, the aggregate nature of the system is not predictable from isolated components but occurs through the interaction of multiple components (Hmelo-Silver and Azevedo 2006). As Hmelo-Silver and Azevedo pointed out, many complex systems can be viewed as emergent or causal depending on the point of view one is taking. This view is consistent with Chi's viewpoint on the human circulatory system. In their article, Hmelo-Silver and Azevedo claimed that the human circulatory system is emergent at one level, that is, the cells combine to produce a complex system. At another level, structure-behavior-function representations can also be used to describe the system in causal terms. It is not surprising that most people understand complex systems as collections of parts with little understanding of how the overall systems work (Hmelo-Silver et al. 2007; Hmelo-Silver and Pfeffer 2004 cited in Hmelo-Silver and Azevedo 2006).

Whitesides and Ismagilov (1999) claim that it is important to understand "how the properties of single molecules aggregate into the familiar averaged properties of macroscopic samples of chemicals *because* it will help to tease apart the threads of complexity in chemical systems." In addition, they stated that:

> Chemistry has relied heavily on the ability of ensemble properties that are obtained through thermodynamics and statistical mechanics to make it unnecessary to consider the behavior of individual molecules. Single-molecule chemistry is, however, now making it possible to inquire about the variety of individual molecular behaviors. (Whitesides and Ismagilov 1999, p. 91)

Mental Models

In the past 30 years, more and more researchers have explored the meanings of mental models in order to explicitly provide different perspectives on definitions of mental models. For instance, Gilbert and Boulter (1998) defined a model as a representation of an idea, object, event, process, or system. Vosniadou (1994) stated that a mental model "refers to a special kind of mental representation, an analog representation, which individuals generate during cognitive functioning, and which has the special characteristic that it preserves the structure of the thing it is supposed to represent" (p. 48). To be specific, Vosniadou claimed that the mental models individuals generate or retrieve during cognitive functioning are the points at which new information is incorporated into their knowledge base. As such, a mental model can constrain the knowledge acquisition process in ways similar to beliefs and presuppositions. More specifically, Vosniadou (1994) stated that:

> Mental models are dynamic and generative representations which can be manipulated mentally to provide causal explanations of physical phenomena and make predictions about

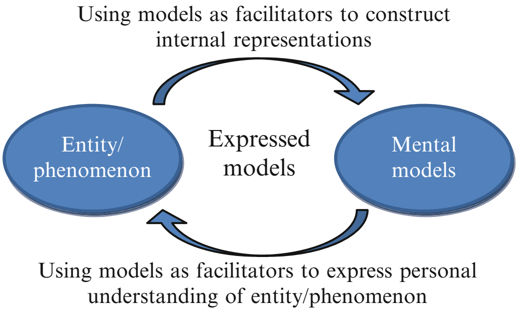


Fig. 2 Relations among expressed models, mental models, and entity/phenomenon

the state of affairs in the physical world. It is assumed that most mental models are created on the spot to deal with the demands of specific problem-solving situations. (p. 48)

In their famous study on investigating students' conceptions, Vosniadou and Brewer (1994) found that children held internally consistent models when they answered questions related to day and night. Ioannides and Vosniadou (2002) further supported this claim in their study on students' explanations of the meanings of force. However, this claim was challenged by diSessa et al. (2004) who replicated the study and argued that they failed to find consistent explanations as Ioannides and Vosniadou claimed, and, therefore, diSessa et al. concluded that "students' ideas are not random and chaotic; but neither are they simply described and strongly systematic" (p. 843).

Buckley and Boulter (2000) stated the functions of mental models, asserting that they are used both to understand and to create expressed models that influence our perceptions of phenomena. By definition, expressed models represent selected aspects of phenomena and of our mental models. Chiu and Liu (2008) simplified the relation among phenomenon or real objects, models, and mental models as shown in Fig. 2. In Fig. 2, expressed models act as facilitators to help learners construct internal representations (e.g., mental models), while on the other hand, mental models can also be used to express personal understanding of phenomena or scientific concepts via the use of models.

Chi et al. (1994) described two types of mental models that exist in opposition to the correct scientific model, namely, fragmented mental model and flawed mental model. The former is normatively incorrect and cannot be used to make systematic predictions or generate sensible and consistent explanations. The components of the latter are also incorrect but nevertheless coherently organized.

Vosniadou et al. (2001) claimed that the ability to form mental models is a basic characteristic of the human cognitive system, and that even young children can construct mental models which have predictive and explanatory power and can be used as mediating mechanisms for the revision of existing knowledge and the construction of new knowledge. Not only can we form mental models of the physical environment, we can also use these representations as a basis for the creation of tools and artifacts that can then in turn be used as external, prosthetic devices in thinking (Stathopoulou and Vosniadou 2007). Mental models play an important role in conceptual change exactly because they are the point where new information enters the cognitive system in ways that can modify what we already know. They can bring together representations based on physical reality with cultural representations based on scientific explanations of physical reality and cultural artifacts (Stathopoulou and Vosniadou 2007).

In sum, we believe mental models have some flaws and incomplete knowledge, but their consistency is necessary for problem solving and conceptual understanding. In our studies, we use empirical evidence to support our position on the nature of mental models and their role in the process of learning. In this work, mental models represent students' conceptions of gas particles that were obtained while interviewing students or from students' responses to diagnostic test items. The mental representations we inferred from the interview data and the quantitative data were reinterpreted via the pictorial representations of the students' understanding. In order to uncover what conceptual change occurred and what the progressive pathway involved was, we included the RAINBOW approach to answer these questions and then used the approach to investigate what the analysis of the students' performance could reveal.

Learning and Teaching of Gas Particles

In the following sections, we discuss a study that involved a six-session instruction of an intervention in which students engaged in multiple modeling activities about gas particle behavior and distributions. It is used to illustrate how mental models and conceptual change were examined and what solutions we have found to explain students' difficulties in learning science as well as the possible pathways that we propose for textbook writers and educators in the future.

Investigating Students' Conceptions of Gas Particles

Following a series of studies investigating secondary school students' understanding of gas particle behavior and distribution (i.e., Chiu and Chung 2008, 2009), we were able to document and identify typical patterns of incorrect and incomplete mental models that students commonly use to solve problems related to diffusion as well as their correct or theory-like mental models about gases. In this section, we highlight some important findings to illustrate the value of the RAINBOW approach in conceptual change research.

Participants. An entire class with 33 11th graders was involved in multiple modeling activities as a treatment group, whereas 26 11th grade students were treated as a comparative group with regular activities in chemistry class. The majority of the students were aged 16–17, from middle socioeconomic status, and scored around 50 % on the high school national entrance examination.

Research design. In order to design activities for learning science, we adopted Boulter and Buckley's (2000) five modes of representation that are significant to

Table 2 Instructional design of multiple representations for the modeling group

Instructional period	Contents	Activities	Modes of modeling representation
1st	Explaining random movement and distribution of particles	Dynamic models for particle motion	Concrete/mixed
2nd	Explaining Boyle's law through pulmonary respiratory apparatus	Needle and balloon experiment	Concrete/mixed
3rd	Explaining Boyle's law and Charles's law through computer simulation	Computer simulation experiment	Visual/mixed
4th	Explaining that (1) particles move randomly during diffusion and (2) the smaller the molecule is, the faster speed it has	Role-play	Gestural/mixed
5th	Lecturing $PV=k$, $V=kT$, $PV=nRT$, and graphs for their relations	Formula, relational diagrams	Mathematical/ mixed
6th	Using animation software to explain the relation between diffusion and Graham's law in different contexts	Animation instruction and introducing formulas	Visual/mixed Mathematical/ mixed

Fig. 3 The modeling activities in the study

expressed models of any phenomenon: concrete, verbal, visual, mathematical, and gestural modes. Each mode also has its own attributes (such as static vs. dynamic, quantitative/qualitative, deterministic vs. stochastic) of representation to allow for predictable outcomes. Different modes provide different scaffolding structures to the learners. Many modalities suggested were adopted in the activities. The instructional design is listed in Table 2. Six 50-min class periods (across 2 weeks) were used to teach the intended curriculum.

Model-based activities. In the treatment group, the students were actively involved in various formats of modeling activities (Fig. 3). Each activity required students to participate in group work. For instance, the activity shown in the left photo of Fig. 3 required the students to observe how different amounts of gases being pushed into the box from the hair dryer influenced the movement of plastic balls of different sizes in the box. The activity shown in the right photo of Fig. 3 required the female students to represent red dyes at one corner and the male students to represent blue dyes at the other corner. All the students had their eyes covered with their hands and were asked to move around on their own for a minute. Once they took off the handkerchiefs, they found they were randomly distributed in the classroom. Through these activities, the students were able to figure out how molecules move randomly from one place to another. In informal interviews, the students expressed that they had never thought of acting as particles to learn science. They valued these hands-on activities highly for promoting science learning.

Instrument. In this study, we developed a set of computerized diagnostic items to examine students' conceptions regarding the behavior of gases. The test items included two parts. The first part involved: volume of gas vs. movement of gas particles; pressure of gas vs. movement of gas particles; the relation between the partial pressure of gas, the vapor pressure, the diffusion rate, and the movement of gas particles; and the properties of ideal gas. The second part of the test items dealt with: the relation of pressure, volume, and movement of gas particles among mixed gases; factors and microscopic mechanisms for vapor pressures; and the relation of gas particles of movement and diffusion. All the test items were categorized into contextualized or non-contextualized as well as macroscopic or microscopic levels of questions. A computerized program, the Web-Based Mental Models Diagnosis (WMMD) System, was used to detect students' conceptions about the movement and distribution of gas particles (Wang et al. 2013). The WMMD allows us to track students' reasoning along with changes in instruction and helps us to see how consistent, correct, and stable mental models are. Using the computer interface, we first presented the dynamic representations in the microscopic view of the volume and pressure of gas and distribution and movement of gas particles. Second, we designed two-tier generative questions to detect students' original conceptions and traced the answering path of each student. The first-tier items were the observable phenomenon, and the second-tier items were microscopic views about the mechanism of the phenomenon described in the first-tier items. Three professors with chemistry backgrounds and one high school teacher validated the instrument. Thirty-eight 12th graders and 87 11th graders participated in the pilot study. The 11th graders were taught the gas concepts before the experiment. The value of α (coefficient of the test) of this set of test items was 0.81.

Research Findings

Overall Performance

Table 3 shows that the overall performance of students in both groups (paired t-test) increased significantly from the pretest to the posttest. The significant differences were examined by the use of the pretest as covariance for ANCOVA test. The results revealed that there was no significant difference between the two groups on the

Table 3 Performance of students' responses to test items before and after treatment

Sub-concept	Treatment group ($n=33$) Pretest	Posttest	Post-pre (p-value)	Control group ($n=26$) Pretest	Posttest	Post-pre (p-value)	$T-C$ Posttest (p-value)
Pressure/volume	43.4	50.5	.12	36.9	40.4	.21	.049*
Vapor pressure	35.1	50.8	.008**	45.6	51.9	.11	.833
Diffusion	40.2	67.0	.000***	47.1	52.9	.32	.006**
Movement	38.6	89.7	.000***	51.9	76.4	.02*	.000
Ave.	39.2	58.7	.005**	43.6	51.1	.04*	.015

Post-pre means the difference between the sum of each student's lumped sum of scores on that sub-concept's items on the posttest minus the lumped sum of the same items on the pretest
T−C means total posttest scores of the treatment group minus the total posttest scores of the control group
*$p<.05$; **$p<.01$; ***$p<.001$

pretest; however, there existed a significant difference between the treatment and control group in the gained scores between the pretest and the posttest (see Table 3). In particular, a significant difference was found in the two main concepts, namely, diffusion and movement, which we attributed to the greater emphasis on model-based activities.

The following analyses take three perspectives. Four major data analyses of the students' performance were completed: the first was about the students' mental models of mixed gases before and after the multiple modeling activities, the second was about the ontological categories changed from the pretest to the posttest, the third was about the theoretical framework of the gas particles, and the fourth were responses from the students about the model-based activities.

From the Developmental Perspective

Types of students' mental models of mixed gases before and after multiple modeling activities. The students' mental models of mixed gases were categorized into five incorrect conceptualizations and one scientific model as shown in Fig. 4 which highlights the major finding that students conceived of heavier gases as being distributed at lower spaces, while lighter gases are distributed at higher spaces. Figure 5 reveals that close to 50 % of the students in the treatment group changed their mental model to a scientific model after multiple modeling activities; however, only about 25 % of the students in the control group made such a change after the learning activities.

Close to 50 % of the students (45.5 % in the experimental group and 53.8 % in the control group) already held the scientific model before instruction. Among the other five mental models, the one in the middle was the most preferred by all of the students from both groups on the pretest. About one fifth of the students believed that the lighter particles float on top of the container, while the heavier particles sink to the bottom of the container. However, on the posttest, the results revealed that

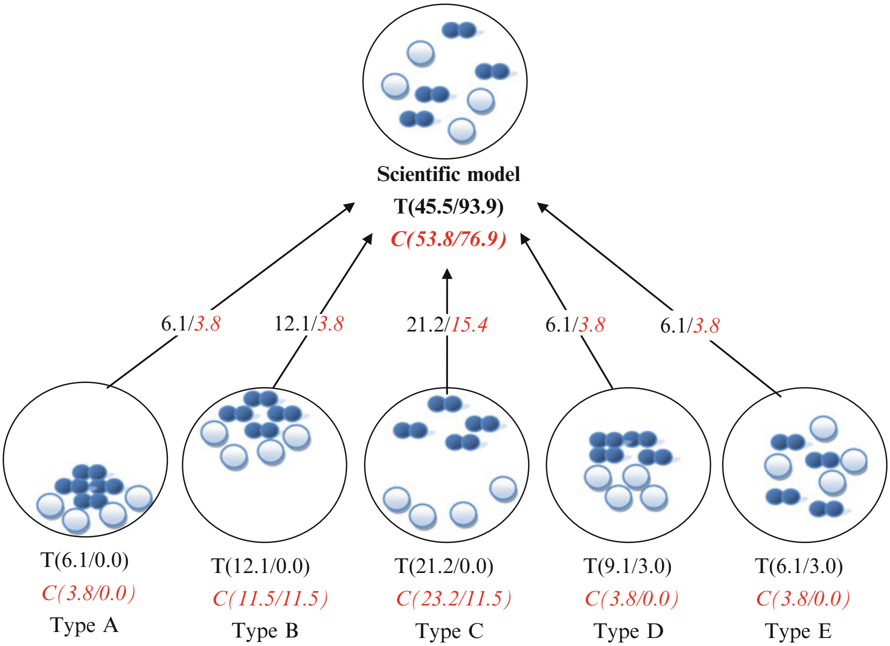


Fig. 4 The path analysis of mental models before and after instruction by control and treatment groups [Note: 1. (pre/post): %; ⟶: from pretest to posttest (only show above 5 %), *T*: for treatment group and C for control group. 2. ●● stands for hydrogen particles, while ○ stands for helium particles]

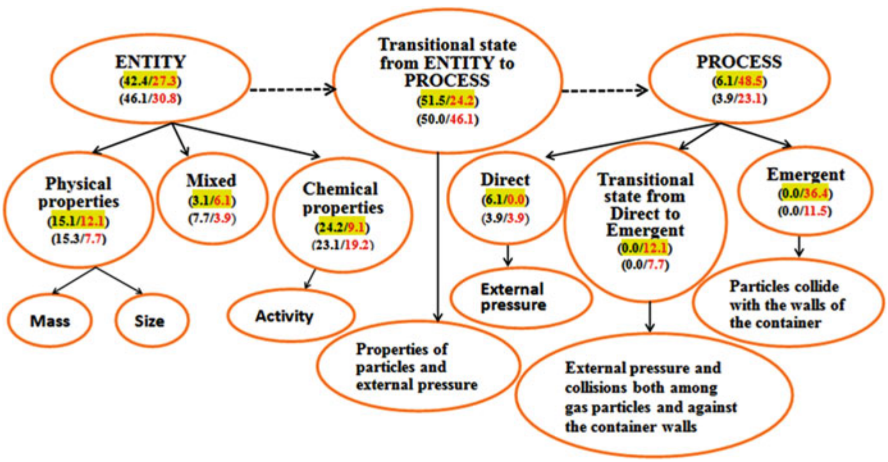


Fig. 5 The ontological tree of concepts students need to know and the percentages of students who demonstrated this knowledge in this study [Note: 1. (a/b) stands for % of a specific model in the pretest/% of a specific model in the posttest; 2. The figures on the *top* are for the treatment group, while the figures at the *bottom* are for the control group]

Table 4 The distribution of students' mental models of gas diffusion rate

		Treatment group		Control group	
Mental models	Descriptions of sub-models	Pretest	Posttest	Pretest	Posttest
1. Scientific model (SM)	1-1. The lighter the weight of the particles, the faster the diffusion rate	6.1	51.5	7.7	23.1
2. Weight model (WM)	2-1. The heavier the weight of the particles, the slower the diffusion rate	6.1	12.1	7.7	0.0
	2-2. The molecular weight is ↗, the pressure is ↗, so the diffusion rate is faster	9.1	3.0	7.7	11.5
3. Activity model (AM)	3-1. The molecular activity is ↗, the pressure is ↗, so the diffusion rate is faster	12.1	3.0	7.7	7.7
	3-2. The molecular activity is ↗, the speed of movement is ↗, so the diffusion rate is faster	21.2	9.1	26.9	3.8
4. Volume model (VM)	4-1. The molecular volume is ↗, the pressure is ↗, so the diffusion rate is faster	3.0	6.1	3.8	3.8
	4-2. The molecular volume is ↗, the move speed is ↗, so the diffusion rate is faster	6.1	3.0	7.7	7.7
5. Energy model (EM)	5-1. The molecular weight is lighter, the kinetic energy is ↗, so the diffusion rate is faster	18.2	9.1	15.4	23.1
	5-2. The molecular weight is ↗, the kinetic energy is ↗, so the diffusion rate is faster	18.2	3.0	15.4	19.2

↗ standing for increasing

none of the students from the treatment group held mental model type B or C, while the students in the control group still held the misconceptions about types B and C that heavier gases sink to the bottom.

Types and Changes of Students' Mental Models of Gas Diffusion

The results showed that the students had five types of mental models regarding gas diffusion and 9 subtypes as shown in Table 4. Table 4 shows that before the experiment started, about 20 % of the students in both groups reported that if molecular activity increases, the speed increases and then the diffusion rate is higher. After modeling instruction, the number of students in the experimental group reporting the scientific model increased from 6.1 % on the pretest to 51.5 % on the posttest. However, the control group went from 7.7 to 23.1 %. As for the activity model, both groups experienced reduced percentages of students holding this type of incorrect model from pretest to the posttest. As for the energy model, 36.4 % of the students in the treatment group on the pretest held this model, but only 12.1 % of these students did on the posttest. However, 30.8 % of the students in the control group held this type of incorrect model, and 42.3 % of the control students mistook the relation between molecular weight, kinetic energy, and diffusion rate. Relatively few students considered the relation among volume, pressure, and diffusion rate. This type of mental model was less developed than the others. The results revealed that the dynamic animation of particle movements facilitated students' understanding of the randomness of motion and the positive relationship between sizes of particles and moving speed.

From the Ontological Perspective

In order to assign the students' conceptions to Chi's ontological categories, we first identified eight concepts in relation to particles from the three ontological categories, namely, Entity, Process, and Mental states. In order to understand the behavior of gas particles, we need to understand the four types of categories, namely, the particulate nature, the behavior pattern of particles, the interactions among the nature of particles, and the interactions among the behavior of particles. The first includes the sizes, volumes, and weight of the particles. The second refers to the randomness of gas movement. The third refers to the potential interaction between particle components. The fourth characteristic refers to the interaction among the particles in terms of their behavior in that state.

The ontological categories of students' conceptions of gas particles are displayed in Table 5, and then an analysis of ontological categories of conceptual change about the gas particles is presented in Fig. 5. Table 5 is a taxonomy of the ontological categories underlying the properties of particles and the causes of gas pressure divided into ontological categories based upon Chi's theory (i.e., Chi 2005; Chi et al. 1994). Figure 5 depicts how mental models related to the particulate nature of particles change ontologically.

Figure 5 shows that there were transitional states from *Matter* to *Process* as well as from *Direct* to *Emergent* that explain how students' mental models were restructured or repaired during the learning process. We found that over 50 % of the students held their conceptions in a transitional state, including Entity and Process conceptions before instruction. About 42 % of the students mainly held the Entity nature of conceptions. Only 6 % of the students held the correct conceptions for the Process state. However, with well-planned instruction, we found decreasing percentages of students with either Entity or transitional state conceptions. Close to 50 % of the students used Process ontological nature of conceptions to answer the questions. In addition, we found that all four types of concepts were relatively well received by the students. In particular and surprisingly, 36 % of the students were able to comprehend the difficult concepts of emergent processes which were not developed at all before the instruction. In other words, the students were able to differentiate the

Table 5 The classification and comparison of specific properties of students' ontological categories

	Properties of particle	Movement of particle	Causes of gas pressure	Effects of gas pressure
Entity – physical properties (mass)	Particle size changed	Partly static, partly moving	Gravity Gravity acting on the particles results in pressure	a b m m Pa>Pb Greater the weight, greater the pressure
Entity – chemical properties (activity)	Particle size changed	Partly static, partly moving	Particles squeezing each other results in pressure	a b v V Pa<Pb Greater the activity greater the pressure
Transitional state from entity to process	Particle size unchanged	Partly static, partly moving	External Force External forces causing pressure	a b m m Pa>Pb Greater the weight, greater the pressure
Direct process	Particle size unchanged	All moving around (randomness)	External Force External forces causing pressure	Fa Fb Pa=Pb $\because F_a = F_b$ $\therefore P_a = P_b$
Transitional state from direct to emergent	Particle size unchanged	All moving around (randomness)	Colliding with each other Particles colliding with each other results in pressure	a b v V Pa<Pb Greater the speed, greater the pressure
Emergent Process	Particle size unchanged	All moving around (randomness)	Colliding with the wall Particles colliding with the wall results in pressure	a b $\frac{1}{2}mv^2$ $\frac{1}{2}mv^2$ Pa=Pb $\because Ek_a = Ek_b$ $\therefore P_a = P_b$

individual particle's movement from the aggregated level which means each individual particle moves around independently from the others so the gas particles filled the container and bounced to each other to make it homogeneous at the macroscopic level. The particles also traveled to each other's spaces. This implies that the particles moved and interacted with each other with no specific direction. Furthermore and interestingly, we found that our students considered the particles moving as a whole instead of viewing some particles as moving while other particles were motionless.

These results reveal the success of the instruction that was designed to take the students' prior knowledge into account to confront the difficulties of learning the emergent processes. The role-play activity was the most influential intervention to help the students understand the randomness and interaction among the particles that allows the two kinds of particles to travel to each other's places simultaneously and endlessly even at the equilibrium state. This implied that the students were able to comprehend how the dynamic nature and behavior of gas particles act in a diffusion context after involvement in multiple representation activities. Their conceptions did not move directly from Entity to Process as Chi predicted; instead, their conceptions were changed gradually from Entity, transition state, and then to Process. Similar results were also found between the Direct and Emergent categories.

This research puts us one step closer to understanding the ontological changes in students' mental models via a series of dynamic assessment tools on gas particles. Also, these outcomes were encouraging because they suggest the incremental development of a pathway for students' learning about gas particles that allows teachers to bridge students' prior knowledge with the intended knowledge for learning. From this perspective, we found multiple modeling activities helped students develop more emergent conceptions (e.g., the dynamic movement of particles) and that these activities have not been fully discussed in other research studies (see Fig. 5). This will be discussed further.

From the students' demonstrated abilities for constructing mental models about complicated scientific concepts, we found that with the appropriate design of the modeling activities, the students were able to develop meaningful and coherent internal models for learning science (Chiu 2007a, b, 2008; Chiu and Chung 2008). This research puts us one step closer to understanding the ontological changes in students' mental models via a series of dynamic assessment tools on gas particles. The ontological approach adopts the incompatibility hypothesis of Chi and her colleagues (e.g., Chi 1992, 2005; Chi and Roscoe 2002; Chi et al. 1994) in which conceptual change is the process of shifting concepts across ontological boundaries, namely, from matter to process or from causal to emergent processes of an assigned category of a scientific concept. This reassignment process requires learners to reassign a concept to a completely different ontological category.

From the Affective/Social Perspective

From the questionnaire of attitude toward the model-based activities, we found that 48.7 % of the students in the experimental group expressed their most preferred activity was the role-play and 41 % of these students expressed that their most memorable activity was also the role-play. The combination of teachers' oral explanations along with the students' use of body movements allowed the students to effectively construct and imagine the concept of randomization of particles in a container. The role-play activity was designed for all the students to get involved which had never happened before in their science classes. Some students commented that they believed the role-play was appealing and successful because:

> I never knew human being could act as particles. Very impressive and pretty easy to understand the randomization.
>
> It is so much fun to play and to learn chemistry simultaneously.
>
> To understand that different weight causing different diffusion rate via personal experience

The positive feedback from the experimental group revealed that the model-based approach can promote students' conceptual change and also arouse students' motivation for conceptualizing abstract and complex science concepts. Conceptual change cannot rely solely on cognitive apprenticeship (Vosniadou et al. 2008) but must also include intentional and affective involvement to create the social-cultural learning environment that is necessary for science learning (Sinatra and Mason 2008).

Concluding Remarks and Implications

The results show that multiple representations (simulations, role-plays, diagrams, etc.) promote students' learning of particular abstract concepts like gas diffusion. In particular, such representations facilitate construction of mental models of dynamic concepts. In sum, there are three major conclusions.

First, as Chi (2005) appeals, although it is relevant to understand that students' knowledge can be fragmented or coherent in science learning, it is more important "to focus on explaining why some misconceptions may be more entrenched than others" (p. 171). We agree with her claims and designed a series of empirical studies to support her theory with evidence for explaining why students have difficulty learning the interactions among particles and which conceptions, such as the sizes of particles, are relatively remedied by well-designed instructional activities. Although the role-play and other model-based activities improved the students' outcomes on the posttest, we found that the randomness of particle movement and factors influencing particle behavior were difficult conceptions to be reconstructed or removed. This study offers some preliminary evidence that the ontological approach more successfully removes students' incorrect mental models and constructs correct or theory-like mental models in learning science. But profound analyses of students' conceptions are yet needed for further explanations.

Second, Vosniadou's proposal on the importance of the epistemological approach is essential to understanding students' difficulties in learning scientific concepts, in particular, the merit of the presupposition idea. Although sometimes it is a challenge to identify presuppositions in students' understanding of scientific phenomena, we are convinced that it is an effective approach to solving problems and constructing correct mental models. Diagnosing the constraints that hinder students from constructing and reconstructing correct and functional mental models continues to be our focus in conducting research for science learning.

Third, Jacobson and Wilensky (2006) advocated that "from approximately middle school through college (one) can learn and benefit from important concepts and perspectives related to the scientific study of complex systems" (p. 19). We believe the earlier emergent concepts are introduced the better. However, it depends on how the instructional materials and activities are introduced to young learners. Hmelo-Silver and Azevedo's (2006, p. 54) points regarding learning about complex systems and how to support learning about complex systems are key research issues for the learning sciences, and we have identified a host of challenges that learning scientists must come to terms with if we are to help students understand particular complex systems and the notion of complex systems in general.

Implications for Chemistry Education

As for educational implications, we propose four possible directions. First, in terms of theories, multiple theories are available in the area of conceptual change (i.e., Carey 1985; Chi 2008; diSessa 2008; Vosniadou 2008). Our series of experiments prove that taking the ontological, epistemological, and modeling approaches is successful for eliciting students' deep understanding of complex systems, like the behavior of gas particles. Continuous efforts to design activities to promote conceptual change in science learning should be advocated. So, future research will bring us closer to clarifying the pros and cons of multiple theories of science learning. Second, advocating model-based teaching-learning strategies should be the emphasis of current chemistry education in practice. Third, strengthening the connections between different perspectives on learning chemistry is needed. Finally, teacher professional development in the area of students' difficulties and curriculum design in science should be promoted in practice. The link between research and practice should be strengthened to extend the impact of research to the classroom. Each implication is described below.

Investigating Students' Alternative Conceptions Based Upon Conceptual Change Theories

The contribution of this research is to integrate different conceptual change approaches to investigate the types of common difficulties students experience in conceptualizing the behavior of gas particles. The developmental perspective shows the progression of students' concept formation via the use of a model-based approach. Chi's theory allowed us to identify the ontological nature of alternative conceptions held by the students. In addition, transitional stages between direct and emergent ontological trees were discovered that were not mentioned in previous studies. Besides these ontological perspectives, the affective perspective allowed us to see how the model-based activities promoted students' cognitive understanding and aroused their motivation for science learning. A single approach cannot explain all that was going on in the classroom. The results from a series of studies echo the claims of Chi and Roscoe (2002) and Vosniadou and her colleagues (Ioannides and Vosniadou 2002; Vosniadou and Brewer 1994), who advocate that students hold consistent mental models that influence their learning of new information. However, in our study, we found two phenomena to differentiate how consistency issues could be explained. One was that if the students solved isomorphic problems, they tended to show their consistency in using the same mental model. However, if they faced problems in different contexts, inconsistency in using their mental models was found (Liang et al. 2011). The former is echoing the claim by Vosniadou and her colleagues in their studies. The latter is consistent with diSessa's point of view about students' explanation of phenomena. As stated before, we are convinced that the complexity and abstraction of science concepts are not the sole causes of difficulty in learning the behavior of particulate matter. Potential attributes, such as ontological and presuppositional perspectives for these difficulties should also be taken into account to widen our understanding of the difficulty associated with learning scientific concepts at the microscopic level. Therefore, RAINBOW took multiple approaches to differentiate and to explain why and how one concept was more difficult than another for students to accurately comprehend.

Effective Model-Based Teaching-Learning Strategies

Many studies have shown that model-based or model-modeling approaches provide useful opportunities for learners to construct internal representations that help them make connections between models and scientific theories at different levels (Chiu et al. 2011; Chiu and Wu 2009; Harrisonn and Treagust 1996; Justi and Gilbert 2000; Vosniadou et al. 2001). In particular, different models complement each other; therefore, multiple formats of models appear to expand their power and influence in helping learners build scientific models and connect their mental models to coherent structures of theories. In our study, we found that daily life examples (e.g., using Styrofoam and hair dryers to simulate molecular movement), role-play, and animation were successful in facilitating the students' conceptual change toward more scientific models. Using various modalities (agent, physical objects, event, process) provided different modes and contexts for learning and allowed for individual as well as small group interaction. This focus gave the students opportunities to use models, representational symbols, manipulative objects, and even their own bodies.

Relationship Among Phenomena, Symbols, Microscopic View, Sociocultural Impact, and Language

In our study, we found the multiple representations approach successfully aided students in making links between model-based activities and conceptual understanding of behaviors of gas particles. This study not only opens a new avenue of

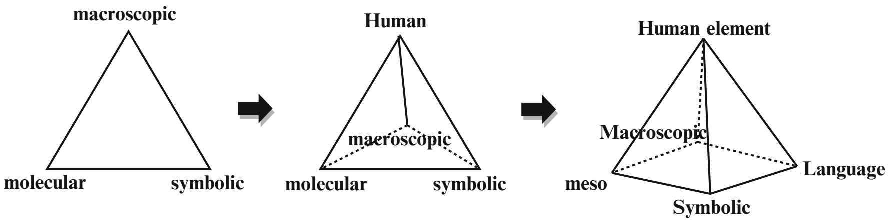


Fig. 6 The relationships among several factors

methodological taxonomy in analyzing students' knowledge structure of gas particles, but it also echoes the important role of triplet relations among symbols, macroscopic, and microscopic views of phenomenon as proposed by researchers. For instance, in Johnstone's (1993) famous triangle of learning levels in chemistry education, there are three basic elements, namely, macro-, sub-micro, and representation. Johnstone pointed out that professional chemists work well inside the triangle; however, it might be a challenge for learners who lack knowledge in connection with these components to learn chemistry. "No one form is superior to another, but each one complements the other" (Johnstone 2000). Also, experienced chemists can manipulate all three components simultaneously, but this is not so easy for learners due to their unfamiliarity with these three components and their limited capacity of working memories (Johnstone 2000). Mahaffy (2006) proposed rehybridizing the planar triangular metaphor for learning chemistry into a tetrahedron (Fig. 6) in which the new element of human contexts for chemistry was taken into account. In other words, human beings, such as students, who create substances and culture, are needed to be situated for authentic learning of chemistry. Chiu (2012) further added the component, language, to the tetrahedron model to express its role in helping or restricting learners' views of the world and meaning of words. The meaning of words used in daily life is sometimes inconsistent with their scientific definition and use. For instance, the Chinese character for hydrogen (氫) implies two meanings, namely, gas and light. Although the lightness helps students to understand hydrogen has small molecular mass and that it readily floats, students mistake this meaning when the context is a small container and fail to understand the principle of randomness.

Gilbert and Treagust (2009) challenged the terms of "type" used for macro, submicro, and symbolic representations and then advocated "level" instead for two reasons. First, "level" can have the meaning of scale/size/measure to be used for introducing intermediate (i.e., meso) representations as well as for explaining and predicting phenomena. Second, "level" implies a change from concrete familiar language to abstract chemical language in a short, concise, reduced form for communication purposes. On the one hand, we agreed with Gilbert and Treagust's advocacy for meta-visual fluency. On the other hand, we advocate for relating quintuplet relations as shown in Fig. 6 as the important chemistry competence to be promoted.

Pedagogical Content Knowledge in Chemistry (PCK-C)

From our past studies related to students' conceptions of gas particles, we repeatedly found that students held alternative or misconceptions that were in parallel with scientific concepts. We wonder how well teachers understand students' conceptions of gas particle behavior. Liang et al. (2011) collected data from 102 eighth graders and 92 ninth graders and 31 physical science teachers in junior high schools in Taiwan. They found four major types of mental models held by the students, namely, weight model, size model, pressure model, and scientific model. However, the results showed that the physical science teachers could not predict accurately the students' understanding of the behavior of gas particles because they underestimated the effect of the pressure influencing students' performance on test items. In informal interviews, the teachers expressed that traditional multiple-choice items can hardly uncover the difficulty their students confront or the underlying structure of their students' knowledge. Therefore, precise predictions by the teachers could not be made. In addition, we wonder whether teachers held misunderstandings about gas diffusion, like their students, that influenced their predictions of students' conceptions of diffusion. On the other hand, teachers rarely "interview" their students; therefore, teachers usually only know the errors their students make but not the underlying arguments for why these mistakes are made. Promoting teacher professional development in the area of understanding students' alternative conceptions in science practice via the use of research results should be a continuous effort in chemistry education.

Acknowledgment We would like to thank the National Science Council in Taiwan for four grants which supported the study discussed in this chapter (NSC-95-2511-S-003-024-MY2, NSC 95-2511-S-003-025-MY2, NSC 97-2511-S-003-025-MY2, NSC-99-2511-S-003-024-MY3).

References

Adadan, E., Trundle, K. C., & Irving, K. E. (2010). Exploring Grade 11 students' conceptual pathways of the particulate nature of matter in the context of multirepresentational instruction. *Journal of Research in Science Teaching, 47*(8), 1004–1035.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education, 63*, 64–66.

Boccara, N. (2010). *Modeling complex system*. Dordrecht: Springer.

Boulter, C. J., & Buckley, B. C. (2000). Constructing a typology of models for science education. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 41–57). Dordrecht: Kluwer Academic.

Buckley, B. C., & Boulter, C. J. (2000). Investigating the role of representations and expressed models in building mental models. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 119–135). Dordrecht: Kluwer Academic.

Carey, S. (1985). *Conceptual change in childhood*. Cambridge, MA: The MIT Press.

Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. Giere (Ed.), *Cognitive models of science: Minnesota studies in the philosophy of science* (pp. 129–186). Minneapolis: University of Minnesota Press.

Chi, M. T. H. (1997). Creativity: Shifting across ontological categories flexibly. In T. B. Ward, S. M. Smith, & J. Vaid (Eds.), *Conceptual structures and processes: Emergence, discovery and change* (pp. 209–234). Washington, DC: American Psychological Association.

Chi, M. T. H. (2005). Common sense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences, 14*(2), 161–199.

Chi, M. T. H. (2008). Three types of conceptual change: Belief revision, mental model transformation, and categorical shift. In S. Vosniadou (Ed.), *Handbook of research on conceptual change* (pp. 61–82). Hillsdale: Erlbaum.

Chi, M. T. H., & Roscoe, R. D. (2002). The processes and challenges of conceptual change. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change, issues in theory and practice* (pp. 3–27). Dordrecht: Kluwer Academic.

Chi, M. T. H., Slotta, J. D., & de Leeuw, N. (1994). From things to processes: A theory of conceptual change for learning science concepts. *Learning and Instruction, 4*, 27–43.

Chi, M. T. H., Siler, S. A., & Jeoung, H. (2004). Can tutors monitor students' understanding accurately? *Cognition and Instruction, 22*(3), 363–387.

Chiu, M. H. (2007a). A national survey of students' conceptions of chemistry in Taiwan. *International Journal of Science Education, 29*(4), 421–452.

Chiu, M. H. (2007b, July). *Research And InstructioN-Based/Oriented Work (RAINBOW) for conceptual change in science learning.* Paper presented at the 2nd Network for Inter-Asian Chemistry Educators Symposium, Taipei.

Chiu, M. H. (2008, 29 March–2 April). *Research And Instruction-Based/Oriented Work (RAINBOW) for conceptual change in science learning—An example of students' understanding of gas particles.* Paper presented at the NARST 2008, Baltimore.

Chiu, M. H. (2012). Localization, regionalization, and globalization of chemistry education. *Australian Journal of Education in Chemistry, 72*, 23–29.

Chiu, M. H. & Chung, S. L (2008). *Students' ontological conceptual change on the topic of gas particles via the use of the Research and Instruction-based/oriented work (RAINBOW) approach*. Paper presented at the EARLI, 6th International Conference on Conceptual Change, Turku.

Chiu, M. H., & Chung, S. L. (2009, 31 August–4 September). *Investigating students' ontological change in their mental models of gas particles*. Paper presented at European Science Education Research Association (ESERA), Istanbul.

Chiu, M. H., & Lin, J. W. (2008). Research on learning and teaching of students' conceptions in science. In I. V. Eriksson (Ed.), *Science education in the 21st century* (pp. 291–316). New York: Nova Science.

Chiu, M. H., & Liu, C. K. (2008). From science learning points of view to explore mental model and modeling ability in science education. *Monthly Journal of Science Education (in Chinese), 314*, 2–20.

Chiu, M. H., & Wu, H. K. (2009). The roles of multimedia in the teaching and learning of the triplet relationship in chemistry. In J. K. Gilbert & D. Treagust (Eds.), *Multiple representations in chemical education* (Vol. 4, pp. 251–283). Dordrecht: Springer.

Chiu, M. H., Wang, T. H., Chung, S. L., & Li, H. P. (2011, September). *Using Web-based mental model diagnostic system to investigate students' conceptual change in learning gas particles*. Paper presented at the Biannual Conference of the European Science Education Research Association (ESERA) 2011: Science learning and Citizenship, Lyon.

diSessa, A. (2008). A bird's-eye view of the "pieces" vs. "coherence" controversy (From the "Pieces" side of the fence.). In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 35–60). New York: Taylor & Francis.

diSessa, A. A., Gillespie, N. M., & Esterly, J. B. (2004). Coherence versus fragmentation in the development of the concept of force. *Cognitive Science, 28*(6), 843–900.

Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education, 25*(6), 671–688.

Franco, A. G., & Taber, K. S. (2009). Secondary students' thinking about familiar phenomena: Learners' explanations from a curriculum context where 'particles' is a key idea for organising teaching and learning. *International Journal of Science Education, 31*(14), 1917–1952.

Gilbert, J. K., & Boulter, C. (1998). Models in explanations, Part 1: Horses for courses? *International Journal of Science Education, 20*(1), 83–97.
Gilbert, J. K., & Treagust, D. (Eds.). (2009). Towards a coherent model for macro, submicro and symbolic representations in chemical education. In *Multiple representations in chemical education* (pp. 333–350). Dordrecht: Springer.
Griffiths, A. K., & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*(6), 611–628.
Harrison, A. G., & Treagust, D. F. (2002). The particulate nature of matter: Challenges in understanding the submicroscopic world. In J. K. Gilbert, O. De Jong, R. Justi, D. F. Treagust, & J. H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 213–234). Dordrecht: Kluwer Academic.
Harrisonn, A. G., & Treagust, D. (1996). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. *Science Education, 80*(5), 509–534.
Hmelo-Silver, C. E., & Azevedo, R. (2006). Understanding complex systems: Some core challenges. *The Journal of the Learning Sciences, 15*(1), 53–61.
Hmelo-Silver, C. E., & Pfeffer, M. G. (2004). Comparing expert and novice understanding of a complex system from the perspective of structures, behaviors, and functions. *Cognitive Science, 28*, 127–138.
Hmelo-Silver, C. E., Marathe, S., & Liu, L. (2007). Fish swim, rocks sit, and lungs breathe: Expert-novice understanding of complex systems. *Journal of the Learning Sciences, 16*, 307–331.
Ioannides, C., & Vosniadou, C. (2002). The changing meanings of force. *Cognitive Science, 2*, 5–61.
Jacobson, M. J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *The Journal of the Learning Sciences, 15*(1), 11–34.
Johnson, P. M. (1998). Progression in children's understanding of a "basic" particle theory: A longitudinal study. *International Journal of Science Education, 20*(4), 393–412.
Johnson, P., & Papageorgiou, G. (2010). Rethinking the introduction of particle theory: A substance-based framework. *Journal of Research in Science Teaching, 47*(2), 130–150.
Johnstone, A. H. (1993). The development of chemistry teaching: A changing response to changing demand. *Journal of Chemical Education, 70*(9), 701–705.
Johnstone, A. H. (2000). Teaching of chemistry-logical or psychological? *Chemistry Education Research and Practice in Europe, 1*(1), 9–15.
Justi, R., & Gilbert, J. K. (2000). History and philosophy of science through models: Some challenges in the case of 'the atom'. *International Journal of Science Education, 22*(9), 993–1009.
Lawson, A. E. (1985). A review of research on formal reasoning and science instruction. *Journal of Research in Science Teaching, 22*(7), 569–617.
Liang, J. C., Chou, C. C., & Chiu, M. H. (2011). Student test performances on behavior of gas particles and mismatch of teacher predictions. *Chemistry Education Research and Practice, 12*, 238–250.
Lin, J. W., & Chiu, M. H. (2007). Exploring the characteristics and diverse sources of students' mental models of acids and bases. *International Journal of Science Education, 29*(6), 771–803.
Mahaffy, P. (2006). Moving cemistry education into 3D: A tetrahedral metaphor for understanding chemistry. *Journal of Chemical Education, 83*(1), 49–55.
Margel, H., Eylon, B.-S., & Scherz, Z. (2008). A longitudinal study of junior high school students' conceptions of the structure of materials. *Journal of Research in Science Teaching, 45*(1), 132–152.
Nakhleh, M. B., Samarapungavan, A., & Saglam, Y. (2005). Middle school students' beliefs about matter. *Journal of Research in Science Teaching, 42*(5), 581–612.
Nobes, G., Martin, A. E., & Panagiotaki, G. (2005). The development of scientific knowledge of the earth. *British Journal of Developmental Psychology, 23*, 47–64.
Nussbaum, J., & Novick, S. (1982). Alternative frameworks, conceptual conflict and accommodation: Toward a principled teaching strategy. *Instructional Science, 11*, 183–200.
Papageorgiou, G., Staomvlasis, D., & Johnson, P. M. (2010). Primary teachers' particle ideas and explanations of physical phenomena: Effect of an in-service training course. *International Journal of Science Education, 32*(5), 629–652.

Pintrich, P. R., Marx, R. W., & Boyle, R. A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research, 63*(2), 167–199.
Sinatra, G. M., & Mason, L. (2008). Beyong knowledge: Learner characteristics influencing conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 560–582). New York: Taylor & Francis.
Sinatra, G. M., & Pintrich, P. R. (Eds.). (2003). *Intentional conceptual change*. Mahwah: Erlbaum.
Smith, C. L., Wiser, M., Anderson, C. W., & Krajcik, J. (2006). Implications of research on children's learning for standards and assessment: A proposed learning progression for matter and the atomic-molecular theory. *Measurement: Interdisciplinary Research and Perspective, 4*(1 & 2), 1–98.
Stathopoulou, C., & Vosniadou, S. (2007). Conceptual change in physics and physics related epistemological beliefs: A relationship under scrutiny. In S. Vosniadou, A. Baltas, & X. Vamvakoussi (Eds.), *Re-framing the conceptual change approach in learning and instruction* (pp. 145–165). Amsterdam: Elsevier Press.
Toulmin, S. (1972). *Human understanding: The collective use and evolution of concepts*. Princeton: Princeton University Press.
Treagust, D. F., & Duit, R. (2008). Conceptual change: A discussion of theoretical, methodological and practical challenges for science education. *Cultural Studies of Science Education, 3*(2), 297–328.
Tsitsipis, G., Stamovlasis, D., & Papageorgiou, G. (2009). The effect of three cognitive variables on students' understanding of the particulate nature of matter and its changes of state. *International Journal of Science Education, 32*(8), 987–1016.
Tyson, L. M., Venville, G. J., Harrison, A. G., & Treagust, D. F. (1997). A multi-dimensional framework for interpreting conceptual change in the classroom. *Science Education, 81*, 387–404.
Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*, 45–69.
Vosniadou, S., & Brewer, W. F. (1994). Mental models of the day/night cycle. *Cognitive Science, 18*, 123–183.
Vosniadou, S., & Verschaffel, L. (2004). Extending the conceptual change approach to mathematics learning and teaching. In L. Verschaffel & S. Vosniadou (Guest Eds.), Conceptual Change in Mathematics Learning and Teaching, Special Issue of *Learning and Instruction, 14*(5), 445–451.
Vosniadou, S., Ioannides, C., Dimitrakopoulou, A., & Papademetriou, F. (2001). Designing learning environments to promote conceptual change in science. *Learning and Instruction, 11*, 381–419.
Vosniadou, S., Vamvakoussi, X., & Skopeliti, I. (2008). The framework theory approach to the problem of conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 3–34). New York: Taylor & Francis.
Wang, T. H., Chiu, M. H., Lin, J. W., & Chou, C. C. (2013). Diagnosing students' mental models via the web-based mental models diagnosis (WMMD) system. *British Journal of Educational Technology, 44*(2), E45–E48.
Whitesides, G. M., & Ismagilov, R. F. (1999). Complexity in chemistry. *Science, 284*(5411), 89–92.

The Atom as a Tiny Solar System: Turkish High School Students' Understanding of the Atom in Relation to a Common Teaching Analogy

Canan Nakiboğlu and Keith S. Taber

Introduction

A key aspect of teaching is 'making the unfamiliar familiar', that is, helping learners to understand novel material by finding ways to link to their existing personal knowledge of the world (Ausubel 2000). According to constructivist notions of learning, people use their existing conceptual resources to build new knowledge of the world (Bodner 1986; Glasersfeld 1989; Mintzes et al. 1998; Taber 2009). Many concepts met in science are abstract and cannot be directly demonstrated in classrooms. Teachers therefore commonly introduce such ideas by making comparisons with objects, events or processes that are already familiar to learners (Glynn 1991; Taber 2002b). As Thagard (1992, p. 537) notes, 'good teachers frequently use analogies to render unfamiliar matters comprehensible to their students'.

Teaching and Analogies

One way to introduce unfamiliar ideas, then, is by the use of analogy (Aubusson et al. 2006). An effective teaching analogy involves teaching about *a target* that is unknown to the learners in terms of *a source* that is familiar to them. The terms 'metaphor' and 'analogy' are used in a variety of ways in the science education

C. Nakiboğlu (✉)
Department of Secondary Science and Mathematics Education,
Necatibey Education Faculty, Balıkesir University, Balıkesir, Turkey
e-mail: nakiboglu2002@yahoo.com; canan@balikesir.edu.tr

K.S. Taber
Faculty of Education, University of Cambridge, Cambridge, UK
e-mail: kst24@cam.ac.uk

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_8,

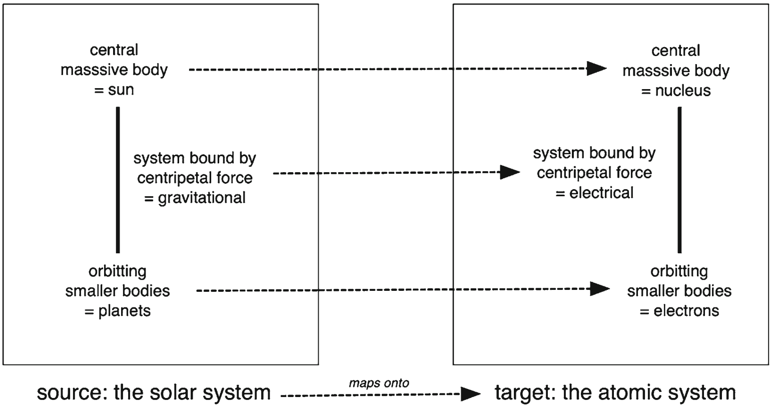


Fig. 1 Mapping from the familiar to the unfamiliar: the basis of the teaching analogy

literature, sometimes interchangeably. Analogy can be distinguished from metaphor in the sense that when using metaphor, A (the target) is said *to be* B (the source), but in analogy, A is said to *be like* B. So if a teacher tells a class that the cell *is* a chemical production plant for the organism, she would be using metaphor, but if she went on to say that the nucleus *is like* the cell's brain, then that would be an analogy. In practice, the intention behind using metaphor and analogy in teaching is often the same, with teachers using metaphor as *implicit* analogies. Teachers may spontaneously use analogy in teaching, without explicitly considering the analogical nature of the process. However, teachers also adopt deliberate and planned teaching models in order to represent curriculum material. There are some teaching analogies that form part of the common repertoire of many teachers, in effect being part of the pedagogical content knowledge of the subject (Coll 2008; Osgood 1960). One such common teaching analogy takes the form that 'an atom is like a tiny solar system' (Taber 2001).

Such analogies can be highly fruitful in both science and science learning. The process of 'analogising' (Bearman et al. 2007) then involves a mapping of features between the analogue (the source) and the target to demonstrate the structural similarities in the two systems. As the similarities occur at the level of *relationships within a structure*, such an approach compares systems rather than discrete entities (e.g. Fig. 1).

It is also accepted, however, that teaching effectively using analogy requires careful planning. As Marcelos and Nagem (2010, p. 606) suggest 'the presence of analogies in teaching in and of itself does not lead to learning [rather] to lead to learning attention about how, for whom and with whom they are utilized and how they are evaluated becomes fundamental'. Reviewing work in this area, Bellocchi and Ritchie (2011, p. 772) offer 'specific conditions [that] must be met in order to produce desirable rather than deleterious results from the use of analogies':

- The analogue concept must be something that is part of students' lived experiences.
- Teachers must make clear that analogies are representations of target concepts and not the target itself.
- Mapping similarities and differences between target and analogue is most important.
- Students must see that the analogy eventually breaks down and is no longer sufficient as a representation of the target concept.
- Multiple models are required to represent fully a target concept due to the limitations of single analogies.

Podolefsky and Finkelstein (2006) suggest that when analogies are used to teach abstract concepts, learners are likely to be cued by specifics of the form or representations used and indeed may sometimes make inferences based on overliteral interpretations of what was meant as merely schematic representation. These findings were obtained in the context of physics learning, an area where many analogies and metaphors are used for communicating abstract ideas (Muldoon 2006). Sarantopoulos and Tsaparlis (2004) suggest that analogies may be especially helpful in supporting lower attainment (cognitive level) students learning about abstract concepts, providing that the teaching offers suitable support in making the intended sense of the analogies.

Yet, research suggests that often analogy is used in science teaching without offering students the explicit support for effective learning (Styles 2003; Treagust et al. 1994). For example, Orgill and Bodner (2006) criticise textbook authors who commonly use implicit analogies without offering readers support in interpreting them, and Marcelos and Nagem (2012) discuss how teachers who consider an evolutionary analogy (the 'tree of life') as a useful teaching resource tend to demonstrate limited understanding of how to effectively incorporate the analogy in their classroom work.

Mapping an Analogy

The basis of analogy is an explicit comparison between two systems that share some level of structural similarity (Gentner 1983). Sometimes a distinction is made between *positive*, *negative* and *neutral* aspects of an analogy (Gilbert and Osborne 1980). For example, in comparing the planetary model of the atom with the solar system, the sun maps onto the atomic nucleus, and planets map onto electrons (see Fig. 1):

Much of the mass of the atom is located at a central point (like in a solar system: *positive* feature).

Electrons repel each other (whereas planets attract each other: *negative* feature).

Only electrons orbit the nucleus (comets and asteroids are *neutral* features which do not map onto the atom).

Analogies and metaphors used in teaching have been called ‘double-edged swords’ because the appropriate knowledge they can generate is often accompanied by alternative conceptions (Bellocchi and Ritchie 2011; Schraw et al. 2007; Smardon 2009; Taber 2005b).

The Nature of the Atom-Solar System Teaching Analogy

Using the analogy that ‘the atom is like a tiny solar system’ as a teaching model can be understood as based on the (perhaps often implicit) premises that (Taber 2001):

1. Secondary age students are generally familiar with the general form of the solar system.
2. The atom is an abstract theoretical entity, and atomic structure is generally unfamiliar to students at the start of secondary school.
3. There are structural similarities between the two systems such that students can be introduced to atomic structure by comparison with their existing knowledge of the solar system.

Where such premises are valid, using the solar system as a teaching analogy seems quite reasonable, at least where the target knowledge here is the particular ‘planetary’ model for the atom. Students who are taught a planetary model of the atom without appreciating its status as a model may well have difficulties later learning about more advanced models (Taber 2005a, 2010).

Although the atom is a key concept in learning about chemistry in school science, many authors report that teaching and learning about the atom and atomic theories in science education are problematic (Nakiboğlu 2008; Niaz et al. 2002; Taber 2003; Tsaparlis 1997). The structure of atom and atomic theories are part of the secondary curriculum and general chemistry courses in many countries. In general, four atomic theories (Thomson, Rutherford, Bohr and quantum mechanical theory) are presented in a sequential manner in many chemistry textbooks. On the other hand, it has been found that students are still using the solar system model or a simple nucleus/electron shell model in explaining the structure of atom, even after being introduced to more advanced models that are more appropriate in particular contexts (Nakiboğlu and Benlikaya 2001; Taber 2005a; Tsaparlis and Papaphotis 2002).

In Turkey, eleventh grade students’ misconceptions and learning difficulties relating to orbital concepts and modern atomic theory were studied by Nakiboğlu and Benlikaya (2001). The findings of this study indicated that 51 % of students used the solar system model or a simple nucleus/electron shell model whilst explaining the atomic structure. Most of these students thought that orbitals were equivalent to orbits or shells. Similar findings were reported by Tsaparlis and Papaphotis (2002) for 12th-grade Greek students who continued to think in terms of the old quantum theory and that the electrons rotate around the nucleus like the planets around the sun. Similar findings were also reported by Taber (2005a) from interviews with 16–19-year-old English college students. However, the context of this chapter is the stage at which a planetary model of the atom is set as target knowledge in the curriculum.

The Familiar: The Solar System

The solar system is commonly part of secondary school science. Students are usually expected to learn about 'our' solar system: our sun, Sol, and its system of planets, with their moons, planetoids and comets. Students will be expected to understand how spatial and dynamic features of the solar system lead to the phenomena of day and night and the seasons on earth and to the phases of the moon and occasional eclipses. Learning in this topic has been well studied in a variety of cultural contexts, and common learning difficulties have been widely reported (Brewer 2008; Nussbaum 1985; Tobias et al. 2007).

Drawing upon the Familiar

As shown in Fig. 2, it is possible to identify some clear positive aspects of the analogy, that is, features of the solar system, that it is productive for students to transfer to support construction of their mental model of the atom. However, despite these similarities, there are clearly many differences between the systems (as is normally the case in any analogy). So there are a number of features of the analogue (solar system) that it would be inappropriate for the student to transfer across to the target (atomic system). That need not undermine the potential usefulness of the comparison, but does suggest that teachers should be careful to explain the positive analogy and to highlight that not all features are analogous.

A Diagnostic Probe

A diagnostic instrument was designed by the second author to elicit student understanding of the (planetary model of the) atomic system and the solar system. The instrument was published as part of a project sponsored by the UK's Royal Society of Chemistry (Taber 2002a, b). During this project classroom teachers administered and provided feedback on the classroom materials, offering some evidence of face validity. When secondary students in the UK were administered the instrument (Taber 2012), it was found that:

> Although students were generally aware that solar systems were bound by gravitational forces, there was a relatively low level of awareness of *the nature of the forces* acting in atomic systems: with a broad range of vague and specific and incorrect suggestions being made.

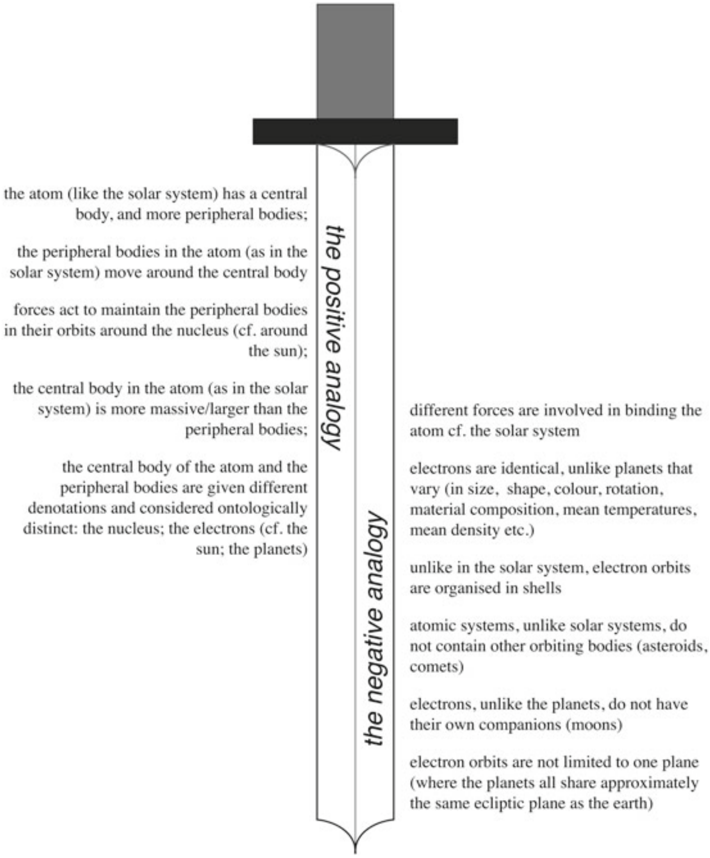


Fig. 2 Positive and negative features of the atom – solar system analogy

Almost half of the sample did not recognise forces acting among the peripheral (orbiting) components of the systems (i.e. force between planets, force between electrons).

Although there was generally a strong recognition that forces decreased with separation of the interacting bodies, only a minority of students recognised that the same magnitude of force acted on two interacting bodies (as per Newton's third law which sees force as an interaction between two bodies, acting with equal magnitude on both).

The pattern of responses was very similar across the two systems when considering both these principles (forces decreasing with separation, equal 'action' and 'reaction' forces).

The findings from the UK study suggested that although students seemed to readily see the two systems as analogous, they demonstrated conceptions of both systems at odds with the canonical understanding presented in the curriculum.

Students' thinking about scientific topics can derive from a range of sources (intuitive knowledge, lifeworld ideas shared in social contexts, interpretations of linguistic cues, formal teaching, etc.) and often likely develops iteratively under a range of influences (see literature reviewed in Taber 2009). Understanding the nature, evolution and influences upon student thinking is important to develop effective pedagogy, and cross-cultural comparisons can offer some insight into such issues (Taber 2008): for example, finding the incidence of different reported common alternative conceptions in populations following different curriculum, taught by different teaching approaches, in different languages, and in social contexts with different common folklore or among social groups holding different worldviews, etc.

Purpose of the Reported Study

As the value of the teaching analogy depends upon (a) familiarity with the source concept, (b) appreciating the negative as well as the positive aspects of the analogy, the present study was designed to explore the extent to which Turkish students understand the nature of the physical interactions in the two systems and the extent to which they perceive the forces acting in the atomic and solar systems in analogous ways.

The previous use of the instrument with British students had suggested that secondary age students held alternative conceptions of the forces acting within the two systems. This in turn reflected research which suggested that students commonly find aspects of mechanics (such as the forces acting in a context such as the solar system) quite counterintuitive (Gilbert and Zylbersztajn 1985; McCloskey 1983; McCloskey et al. 1980; Savinainen and Scott 2002; Watts 1983; Watts and Zylbersztajn 1981), suggesting that for many students the solar system may not provide a sound basis for analogy to other target concepts.

The research questions for the present study were:

1. To what extent do Turkish secondary students perceive forces acting in the atomic and solar systems to be analogous?
2. To what extent are alternative conceptions about the forces acting the atomic and solar systems that have been identified among British students also found among secondary Turkish students?

Methodology

The present study is confirmatory (Biddle and Anderson 1986), in that the instrument used was designed to test out specific ideas that had been suggested in prior research, rather than to explore student thinking about the two systems in broader

Table 1 Structure of the diagnostic probe

Focus	Atomic system	Solar system
Type of force	Electrical (Q1)	Gravitational (Q5)
Effect of distance on force	Outer electron attracted with less force(Q2)	More distant planet attracted with less force (where planet masses are comparable) (Q6)
Reciprocity of forces	Same magnitude force between nucleus and electron (Q3)	Same magnitude forces between sun and planet (Q7)
Force between peripheral bodies	Force between electrons (i.e. repulsion) (Q4)	Force between planets (i.e. attraction) Q8

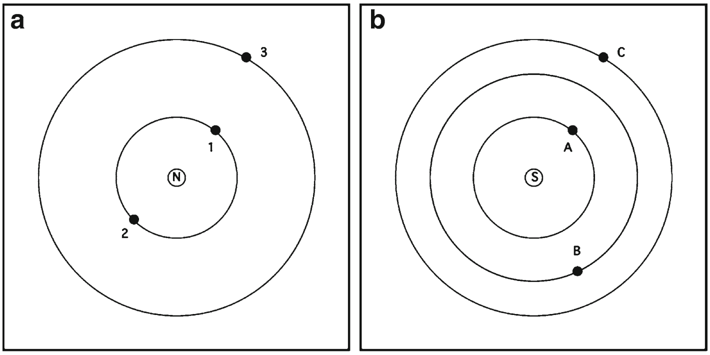


Fig. 3 Focal figures – (**a**) atomic system; (**b**) solar system

terms (i.e. 'discovery' research). The primary methodology of the study is that it takes the form of a survey, where the same set of questions are asked of a sample of respondents considered to be drawn from a particular population – here Turkish secondary age students. In the present study, a translated version of the instrument used in the UK study was administered in Turkish secondary schools. The instrument was translated from English to Turkish by the first author and checked by an English lecturer who taught English. To ensure the content validity of the Turkish version of the instrument, the secondary school curriculum was examined by the first author and also expert judgement was provided by two experienced secondary school chemistry teachers who hold master degrees in chemistry education.

The instrument asked eight closed questions (or fixed-choice questions, Schuman and Presser 1979), supplemented by asking for reasons for the six questions where such a supplementary question was indicated, relating to aspects of the pattern of physical forces in the two systems as summarised in Table 1. The respondents were then asked to list any similarities and differences they were aware of between the two different systems. The original English version of the instrument is reproduced in the Appendix.

The probe included exemplar figures to illustrate the two systems (see Fig. 3a, b), which were designed to be similar in appearance.

Table 2 Sample of respondents

School year (age)	*N*
9 (15-year-olds)	119
10 (16-year-olds)	166
11 (17-year-olds)	93
12 (18-year-olds)	80
Total	**458**

The sample was drawn from upper secondary age (15–18-year-olds) students from six schools in Turkey, as shown in Table 2. In Turkey, there is an 8-year compulsory education that starts with elementary education having five grades (1–5), ages 7–11, and continues with upper elementary education having three grades (6–8), ages 12–14. Secondary school (*lycée* or *high school*) comprises grades 9–12, ages 15–18. Secondary education encompasses different categories of educational institutions, namely, General high schools, Anatolian high schools, Science high schools, Anatolian fine arts high schools, Social sciences schools, Sports high schools and Vocational and Technical high schools where all secondary students follow the same courses up to the end of grade 9. Chemistry is taught as a separate and obligatory course in 9th grade of all high schools. In 10th, 11th and 12th grades, chemistry lessons are taught either obligatory or elective course according to categories of secondary school. All Turkish students in our study took the chemistry lessons as a separate and obligatory course in 10th, 11th and 12th grades. All schools in the study are public schools and are located within the same city, in the west of Turkey. In Turkey, the system of transition to secondary education is administered by the Ministry of Education and involves a student placement examination (SBS). Students are admitted to different categories of educational institutions according to their score on the SBS. The schools were selected from different kind of high schools where chemistry courses were obligatory by taking school mean entry score into account. One school was selected from five General high schools which have very similar mean SBS entry scores; two schools were selected from six Vocational and Technical high schools (one of the schools has higher mean entry score and second one has lower mean entry score); three schools were selected from eight Anatolian high schools to represent the range of mean entry scores among those eight schools.

All students completed the instrument in Turkish, and their responses were analysed by the first author. Exemplar responses provided here are English translations undertaken by the first author. Analysis for the closed questions simply involved tallying responses in the different response categories suggested in the survey instrument. The responses to open-ended items were classified into semantic categories according to the apparent meaning of student responses, drawing upon the analysts' knowledge of the topic area. Such analysis is necessarily interpretive in nature in that inferences are drawn about intended meaning from student responses in terms of inscriptions which are the public representations of the internal mental activity of individual learners (Taber, forthcoming). Readers should bear in mind this caveat when reading our report of the findings from our analysis.

Readers should also keep in mind that the use of survey methodology allows data to be collected from large numbers of informants, but at a cost of not providing the opportunities for in-depth exploration of ideas possible in interviews studies. It is quite likely, for example, that many of the responses we classified as vague when coding students' references to the type of force acting might not have reflected the most detailed or sophisticated answer that could have been obtained in interviews where follow-up questions could be used.

Findings

Forces in the Atomic System

Question 1 asked 'what type of force attracts the electrons towards the nucleus?' The responses to this question are shown in Table 3. Student responses were categorised in terms of the wording they offered, and these categories have been grouped into those which seem reasonable in terms of canonical curriculum science (references to electrical forces and related terms), those which whilst not incorrect are not specific enough to be considered as correct answers and those which are judged incorrect.

As can be seen from Table 3, a wide range of suggestions were made, and less than a third of the sample (140/458) described the force as electrical, or in terms taken as synonymous. A similar proportion of respondents offered only vague responses (e.g. 'attraction'), which did not specify the type of force, whilst the rest were considered incorrect (e.g. 'gravity'). Although the precise merit of some responses could be open to interpretation, it seems clear that most of these secondary age students did not have a clear notion of the type of force primarily responsible for binding the atomic system together.

Force and Separation in the Atomic System

Question 2 asked students 'Is electron 3 attracted to the nucleus by a stronger force, a weaker force, or the same size force as electron 1?' and 'Why do you think this?' The responses to the first part of this question are summarised in Table 4.

Most students (333/458) gave the correct response that the outer electron would be subject to a weaker force, in line with the conventional Coulombic scheme, and most of these explained this with references to the increasing distance: e.g. 'The attracting forces decreases with increasing distance between the electron and the nucleus'.

Interestingly, almost two-thirds (40/62) of the students who thought electron 3 would be subject to a stronger force explained this in terms of a stronger force being *required* to hold the electron at the greater distance, e.g. 'Since the electron 3 is far from nucleus, it is attracted strongly for keeping it'.

Table 3 Student suggestions for the type of force attracting the electrons to the nucleus in the atomic system

Type of force	9th grade (f)	10th grade (f)	11th grade (f)	12th grade (f)	All grades (f, in %)
Electromagnetic	30	3	0	9	42
Electricity/electrical	5	14	9	5	33
Electrostatic	1	0	4	8	13
Attraction between + charge and – charge	4	25	6	9	44
Electrical + gravity	0	2	0	4	6
Electromagnetic + chemical bond	1	0	0	0	1
Electrical + magnetic	0	0	1	0	1
Correct	*41*	*44*	*20*	*35*	*140* (*31*)
Attraction	4	10	19	0	33
Positive/proton	11	50	16	15	92
Charge	0	3	0	0	3
Force from nucleus	4	11	7	4	26
Force	0	4	0	1	5
Negative	5	3	0	1	9
Vague	*24*	*81*	*42*	*21*	*168* (*37*)
Intermolecular	0	2	0	3	5
Chemical bond	8	7	2	0	17
Ion	1	0	0	0	1
Electron	5	3	2	4	14
Atomic	0	4	0	0	4
Magnetism/magnetic	5	4	1	0	10
Gravity	18	7	0	1	26
Chemical-physical	0	2	0	0	2
Apolar	0	1	0	2	3
Rotation	0	1	0	0	1
Electronegativity	1	0	0	1	2
Centrifugal	0	0	1	7	8
Mechanical	0	0	13	0	13
Radioactivity	0	0	1	0	1
Bonding	0	0	1	0	1
Incorrect	*38*	*31*	*21*	*18*	*107* (*23*)
Subtotal	*103*	*156*	*83*	*74*	*415*
No response	12	7	8	6	34
I do not know	1	2	2	0	5
Nonsense	3	1	0	0	4
Total	**119**	**166**	**93**	**80**	**458**

The subtotal shows the number of responses which could be coded in one of our categories
f frequency of responses in category

Newton's Third Law in the Atomic System

Question 3 asked students to select one of four statements relating to the force between the atomic nucleus and electron 2 (as well as give their reasons). According to Newton's framework for mechanics, forces should be understood as mutual

Table 4 Student perceptions of how force changes with separation in the atomic system

Increasing distance leads to	9th grade (f)	10th grade (f)	11th grade (f)	12th grade (f)	All grades (f, in %)
Stronger force	19	23	13	7	62 (13)
Same size	14	12	4	3	33 (7)
Weaker force	78	122	67	66	333 (73)
Subtotal	*111*	*157*	*84*	*76*	*428* (*94*)
No response	2	4	4	0	10
I do not know	0	1	0	0	1
Nonsense	6	4	5	4	19
Total	**119**	**166**	**93**	**80**	**458**

Table 5 Student perceptions of the reciprocity of force between nucleus and electron in an atomic system

	9th grade (f)	10th grade (f)	11th grade (f)	12th grade (f)	All grades (f, in %)
The force attracting the nucleus to electron 2 is larger than the force attracting electron 2 to the nucleus	7	14	9	7	37 (8)
The force attracting the nucleus to electron 2 is the same size as the force attracting electron 2 to the nucleus	49	65	47	41	202 (44)
The force attracting the nucleus to electron 2 is smaller than the force attracting electron 2 to the nucleus	38	40	12	13	103 (22)
There is no force acting on the nucleus attracting it to electron 2	17	33	15	11	76 (17)
Subtotal	*111*	*152*	*83*	*72*	*418* (*91*)
No response	3	1	0	0	4
Select more than one choice	5	13	10	8	36
Total	**119**	**166**	**93**	**80**	**458**

interactions between bodies: that is, when there is a force, it acts on both bodies, and the magnitude of the force is exactly the same on both bodies (although acting in antiparallel directions, i.e. in this case the force on the electron is towards the nucleus and vice versa). The students' responses to this question are summarised in Table 5.

Again, less than half of the respondents selected the correct response here, and even in these cases, the students' explanations suggest it should not be assumed that they understood the reciprocal nature of forces acting on both bodies. Almost half (63/130) of the codable explanations for this correct response were based on a flawed argument about the individual bodies being in equilibrium, e.g. 'If the attracting forces were not the same, they do not keep the equilibrium of atomic system'.

Over half (54/103) of those considering the force on the nucleus to be smaller explained this in terms of the greater mass of the nucleus, e.g. 'Since the mass of nucleus is greater than electron's mass, it would attract strongly'.

Table 6 Student perceptions of the interactions between electrons in an atomic system

Force between electrons?	9th grade (f)	10th grade (f)	11th grade (f)	12th grade (f)	All grades (f, in %)
Yes	81	124	67	62	334 (73)
No	24	33	21	10	88 (19)
Subtotal	*105*	*157*	*88*	*72*	*422* (*92*)
No response	11	7	4	7	29
I do not know	1	2	1	1	5
Nonsense	2	0	0	0	2
Total	**119**	**166**	**93**	**80**	**458**

Forces Between Electrons

Question 4 asked 'Is there any force between electron 1 and electron 3?' (and 'Why do you think this?'). From the perspective of the canonical school science, this is a very simple question: electrons carry negative charges, so clearly any two electrons will repel each other. The responses to this item are summarised in Table 6.

As Table 6 shows, most of the students, almost three-quarters, gave the correct response to this item. Yet, there was still a substantial minority, almost a fifth, who thought there would be no force between the two electrons. Of those students suggesting correctly that there was a force between the electrons, just over a hundred (101) referred to the force being repulsive, but 44 responses specified that this would be an attractive force. Given that we did not ask respondents to specify the direction of the interaction, this leads us to suspect that many others answering 'yes' may also have not appreciated the nature of the interaction between electrons.

Of the 88 students that gave the incorrect response to this item, almost all (41/48) of the codable explanations for this response were based on arguments that:

- There was only *attraction* between the nucleus and electron (17).
- There was no *attracting* force between electrons (9).
- Similar charges *repelled* each other (15).

It would seem that these students identified 'force' in the question only with 'attraction' (e.g. 'there is only attracting force between nucleus and electron'), and at least 15 of these students clearly recognised a repulsion between electrons, yet did not see that as a force. The fundamental principles that physical forces may be either attractive or repulsive, and that similar charges repel each other, did not seem to have been appreciated by many in the sample.

Forces in the Solar System

Question 5 asked 'What type of force attracts the planets towards the sun?' Physics recognises four fundamental types of force, the strong and weak nuclear forces, electromagnetism and gravitational forces. Although gravitational force is – by many orders of magnitude – much the weakest force, it is responsible for binding

Table 7 Student suggestions for the type of force attracting the planets to the sun in the solar system

Type of force	9th grade (f)	10th grade (f)	11th grade (f)	12th grade (f)	All grades (f, in %)
Gravity	82	50	12	18	162
Gravity + magnetic	0	1	0	1	2
Correct	*82*	*51*	*12*	*19*	*164* (*36*)
Attraction	6	29	35	11	81
Field strength	0	2	0	0	2
Sun attraction	3	13	9	22	47
Central force	0	0	6	0	6
Vague	*9*	*44*	*50*	*33*	*136* (*30*)
Electromagnetic/magnetic	11	15	2	6	34
Electron	1	1	0	1	3
Centrifugal	1	0	5	5	11
Electrical	0	1	5	5	11
Electrical + magnetic	0	1	0	0	1
Attraction between + charge and – charge	0	8	0	0	8
Negative and positive	1	4	1	0	6
Nuclear	1	0	0	0	1
Mechanic	0	0	3	0	3
Chemical bond	0	0	2	0	2
Polar	0	0	1	0	1
Light	0	0	1	0	1
Physical	0	2	0	0	2
Incorrect	*15*	*32*	*20*	*17*	*84* (*18*)
Subtotal	*106*	*127*	*82*	*69*	*384*
No response	10	12	9	8	39
I do not know	1	7	0	1	9
Nonsense	2	20	2	2	26
Total	**119**	**166**	**93**	**80**	**458**

solar systems and indeed galactic structures, together, as all 'normal' matter attracts other matter. (In this sense, normal would even include antimatter, which would still gravitationally interact with other matter in an attractive sense.) The notion that it is gravity that binds the earth to the sun and the moon to the earth, for example, would generally be considered to be part of everyday knowledge.

The responses to this question are shown in Table 7.

Again, as for the atomic system, the results suggested that only a minority (36 %) of respondents could offer an adequate characterisation of the force acting. There were again a variety of suggestions, some simply too vague (e.g. 'attraction'), whilst others were just inappropriate (e.g. 'polar' force).

Force and Separation in the Solar System

Question 6 asked students 'Is planet C attracted to the sun by a stronger force, a weaker force, or the same size force as planet A?' (and 'Why do you think this?'). As with

Table 8 Student perceptions of how force changes with separation in the solar system

Increasing distance leads to	9th grade (f)	10th grade (f)	11th grade (f)	12th grade (f)	All grades (f, in %)
Stronger force	19	23	17	8	67 (15)
Same size	17	8	10	1	36 (8)
Weaker force	72	124	57	69	322 (70)
Subtotal	*108*	*155*	*84*	*78*	*425* (*93*)
No response	4	1	2	0	7
I do not know	0	1	2	0	3
Nonsense	7	9	5	2	23
Total	**119**	**166**	**93**	**80**	**458**

question 2, this was designed to see if pupils appreciated how gravitational force decreases with increased separation of the interacting bodies. In the case of the solar system, there is a potential complication, in that – in principle – a more distant planet could be subject to a greater gravitational force from the sun than a closely orbiting planet if it was more massive. We did not expect many pupils to spot this, as it had not been referred to by students in the English sample (Taber 2012). However, as respondents were asked for their reasoning, we were able to check whether any of them factored this into their thinking. From the entire sample, only six of the students made reference to planet masses in explaining their answers. Three students commented to the effect that the magnitude of the forces would depend upon the masses of the two planets being compared, and one responded that it was not possible to answer the question without this information. One student commented 'if the mass of planet C is bigger than the planet A', it would be attracted with bigger force (thus focusing on mass whilst ignoring separation), and the final student correctly noted that 'if the planets have similar masses, attracting force decreases with increasing distance'. The vast majority of respondents made no reference to mass as a confounding factor.

The responses to the first part of this question are summarised in Table 8.

In parallel with Q2, most pupils did expect the planet with the more distant orbit to be subject to a weaker force from the sun, although over a hundred of the respondents chose a different response. Reflecting Q2, most of those giving codable explanations for suggesting the outermost planet would be subject to a *greater* force (54/56) seemed to feel that a greater force would be *required* to bind a more distant planet, e.g. 'The planet C is far from the Sun and since the planet C is held on its orbit by Sun, planet C is attracted with a larger force by Sun'.

Newton's Third Law in the Solar System

Question 7 asked students to select one of four statements relating to the force between the sun and planet B (as well as give their reasons). As with question 3, this tested whether students would apply Newton's third law, the mutual nature of forces as interactions, to the system. The students' responses to this question are summarised in Table 9.

Table 9 Student perceptions of the reciprocity of force between sun and planet in a solar system

	9th grade (f)	10th grade (f)	11th grade (f)	12th grade (f)	All grades (f, in %)
The force attracting the sun to planet B is larger than the force attracting planet B to the sun	10	12	5	6	33 (7)
The force attracting the sun to planet B is the same size as the force attracting planet B to the sun	47	55	45	44	191 (42)
The force attracting the sun to planet B is smaller than the force attracting planet B to the sun	42	56	25	16	139 (30)
There is no force acting on the sun attracting it to planet B	14	31	6	8	59 (13)
Subtotal	*113*	*154*	*81*	*74*	*422* (92)
No response	2	3	0	0	5
Select more than one choice	4	9	12	6	31
Total	**119**	**166**	**93**	**80**	**458**

Table 10 Student perceptions of the interactions between planets in a solar system

Force between planets?	9th grade (f)	10th grade (f)	11th grade (f)	12th grade (f)	All grades (f, in %)
Yes	84	122	78	59	343 (75)
No	24	34	11	11	80 (17)
Subtotal	*108*	*156*	*89*	*70*	*423* (92)
No response	11	8	4	10	33
I do not know	0	2	0	0	2
Nonsense	0	0	0	0	0
Total	**119**	**166**	**93**	**80**	**458**

Although the correct response (that the force acting on both bodies would be the same magnitude) was the most popular answer, it was only chosen by a minority – just over two-fifths – of the respondents. A third of those making an unambiguous choice of response thought that the sun would experience a smaller force, and most (73/78) of the respondents giving codable reasons for this response focused on the sun's greater size/mass, e.g. 'the mass of the Sun is big/heavy'. Again the most popular explanation (41/122 codable responses) for selecting the correct response was based on flawed logic that forces must be equal to maintain equilibrium, e.g. 'for keeping the equilibrium of solar system'.

Forces Between Planets

Question 8 asked 'Is there any force between planet A and planet C?' (and 'Why do you think this?'). As noted above, all bodies in the universe attract all others gravitationally. The responses to this item are summarised in Table 10.

Three-quarters of the sample responded correctly that there would be a force between the planets, although a substantial minority thought otherwise. The most popular reason for *not* thinking so (23 responses) was that the only force in the system was that attracting planets to the sun, e.g. 'there is no attracting force between the planets; the Sun only attracts the planets'. Of those who did recognise the presence of a force between the planets, one of the most popular explanations (55 responses) was again the flawed idea that this maintained equilibrium in the system, e.g. 'for keeping the equilibrium of solar system; So the solar system maintains its order'.

There were also 29 students who selected the correct response, but because they thought that planets (like electrons perhaps) *repelled* each other, e.g. 'there is repulsion force between them in order to not strike each other'. This is quite an interesting response, and at least in some cases, students could perhaps consider planets might repel by analogy with electrons in an atomic system – for example, the student who suggested that 'there is repulsion force between them due to they have negative charge'. (It is also possible that some of those who suggested electrons attract each other in question 4 could be inappropriately mapping in the opposite direction from their knowledge of the solar system.)

Student Perceptions of Similarities and Differences Between the Two Systems

The final questions were open-ended and asked students to list any similarities or differences they perceived between the two systems. There were many interesting suggestions, which space does not allow us to discuss here in any detail. As a flavour of some of the ideas elicited, one student suggests that 'both of them are invisible' was a similarity, leading us to wonder if this was meant to apply to all parts of the solar system! An interesting suggestion for a difference was that 'the solar system has a creation theory, but the atomic model is still conjecture', a rather 'deep' response we felt.

Student responses were categorised into similar statements using a coding system deriving from the analysis (rather than a preconceived one imposed upon responses). Here we report the most popular response categories: those where the frequency of responses was at least 5 % of the sample (i.e. taking the cut-off as 23 students). These response categories are presented in Table 11 for similarities and Table 12 for differences. It should be borne in minds that students' responses here are likely to have been somewhat influenced by previously answering the other sets of questions.

Generally the most popular suggestions for similarities are unremarkable, and some reflect the questions the students had been asked earlier. The third most popular statement is of interest, as this would seem to reflect one of the alternative conceptions elicited in the structured questions, i.e. that the attractive force in the system acted in one direction, from the more massive body to the less massive body, rather than being a mutual interaction. An example of a response in this category

Table 11 Most frequent suggestions for similarities between the systems

Ranking	Response type	Frequency (%)
1	There is an attraction between the central and peripheral bodies	256 (56)
2	Both systems include orbits	173 (38)
3	The central bodies that have greater mass (sun and nucleus) attract other bodies	118 (26)
4	There are the peripheral bodies around the core/centre	74 (16)
5	They maintain their order (or equilibrium of the system) due to attraction forces	51 (11)
6	The attraction force increases with decreasing distance between the central body and the peripheral bodies	50 (11)
7	Similar shape	48 (10)
8	Presence of a core/central body	43 (9)

Table 12 Most frequent suggestions for differences between the systems

Ranking	Response type	Frequency (%)
1	The nature of the forces	119 (26)
2	The scale	94 (21)
3	Two electrons can move on the same orbit, each planet moves on a different orbit	50 (11)
=4	The planets attract each other, but the electrons repel each other	24 (5)
=4	The peripheral bodies are electrons in the atomic system, planets in the solar system	24 (5)

was '*great bodies like sun attract other small bodies*'. There was also reference from some students to the systems being in 'equilibrium' (some of the students' responses in the fifth most popular category of similarities), again reflecting an alternative conception elicited in the earlier structured questions.

There were fewer popular response categories for the differences (perhaps because the structure of the preceding questions highlighted similarities for the respondents). It is interesting that only about a fifth of the students mentioned the difference in scale between an atomic and a solar system (second most frequent response): whether this was simply taken as read or whether the focal images (with the systems represented by the same size images) was a factor can only be conjectured, without follow-up work. That only about a quarter of students suggested the different types of forces involved is perhaps less surprising given that only a minority of students seemed to know about the type of force involved in the two systems.

Discussion: Comparing Responses Across the Two Systems

Our first research question was: To what extent do Turkish secondary students perceive forces acting in the atomic and solar systems to be analogous? Although the eight structured questions did not explicitly refer to the analogy of the atom to a

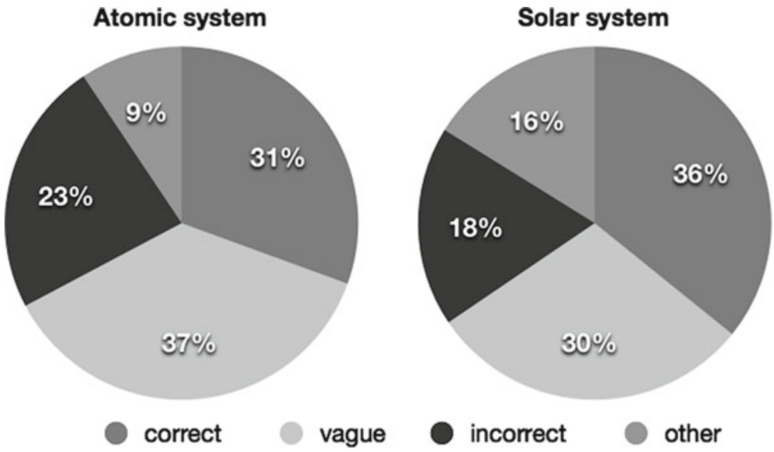


Fig. 4 Student performance on identifying the type of force operating in the two systems

solar system, our motivation in asking students the two sets of parallel questions (and presenting quite similar representations) was to explore their understanding of these systems in the light of the common use of this comparison in teaching. We acknowledge that the structure of the instrument could itself have encouraged some symmetry in responses. In this regard, future researchers intending to use this instrument in research might wish to explore the reliability of the instrument (perhaps by splitting the administration of questions 1–4 and 5–8 on different days and/or reversing the order of the two systems for half of the sample of students).

Questions 1 and 5 asked students to tell us the types of forces acting in the two systems. We suspect that teachers would think that this was a rather basic question and that the vast majority of students in these high school grade levels would be aware that the atom was bound together by the electrical interaction between nucleus and electrons and that the planets orbit the sun because there is a gravitational attraction between all bodies in the universe. In categorising students' responses, what we judged as reasonable variations in student terminology were taken as correct. So not only were *electrical*, *electromagnetic* and *electrostatic* accepted as appropriate terms in the atomic case but also those responses which described the attraction between opposite charges without offering a further label.

Figure 4 compares the relative proportions of those giving correct, vague or incorrect responses (with nonresponses, ambiguous and uncategorisable responses shown as 'other'). In both cases, only minorities of students were able to offer an acceptable response – a little under a third for the atomic system and a little over a third for the solar system.

These results are somewhat different from those attained by Taber (2012) from a sample of English students of comparable ages. In that study it was found that over nine-tenths of the sample could correctly identify gravitational forces acting in the solar system, a considerably higher proportion than in the present study. However, in contrast, only a fifth of the English students were able to offer an acceptable

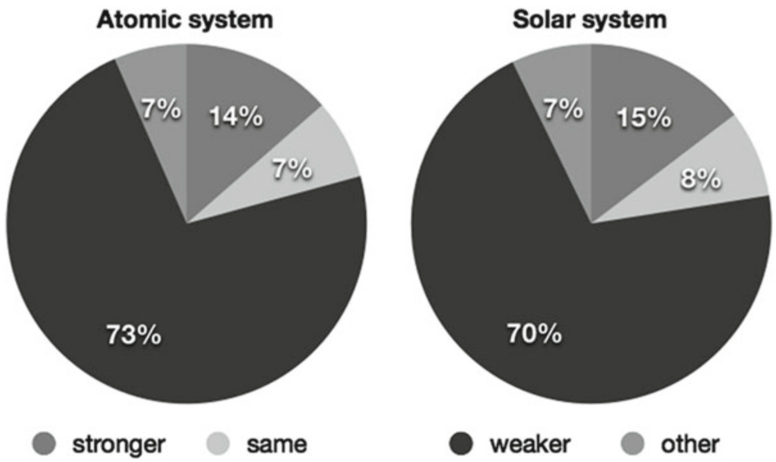


Fig. 5 Student responses to how the magnitude of force depends on the separation of bodies

response in the case of the atomic system, somewhat less than in the present study. Whilst neither study claims a representative sample of the national populations, the difference is large enough to suspect that some cultural or linguistic factor may be involved here – possibly relating to the content, sequencing or emphasis of teaching in the two different curriculum contexts (Taber 2008).

Questions 2 and 6 both asked about the effect of separation on distance. In both systems, force depends upon separation according to an inverse square law; i.e. doubling the separation of an electron from the nucleus, or of a planet from its sun, will lead to the force between them being only a quarter of its previous value. The questions did not ask for a quantitative estimate, but simply for the direction of any effect (i.e. that force gets smaller with greater distance between the bodies).

Figure 5 shows the relative proportions of responses for the force being stronger, unaffected or weaker with increased separation. Clear majorities of students expected force to weaken with greater separation in both cases. Perhaps the higher level of success here reflects the intuitive nature of this pattern: in everyday life pupils commonly experience a situation where an effect decreases with increasing separation (moving away from a fire, moving further from a source of sound, using magnets to pick up metal, etc.).

Questions 3 and 7, however, asked about a feature of forces that is not so intuitive. Our second research question was: To what extent are alternative conceptions about the forces acting in the atomic and solar systems that have been identified among British students also found among secondary Turkish students? A force is an interaction between two bodies, and so the magnitude of the force acting on both bodies is the same. However, the *effect of* the force will also depends upon the masses of those bodies, as the same force has greater effect on a less massive body, and it is this pattern which tends to be more salient (as the effect of forces can often be perceived, when the forces themselves are not). Figure 6 shows the proportions

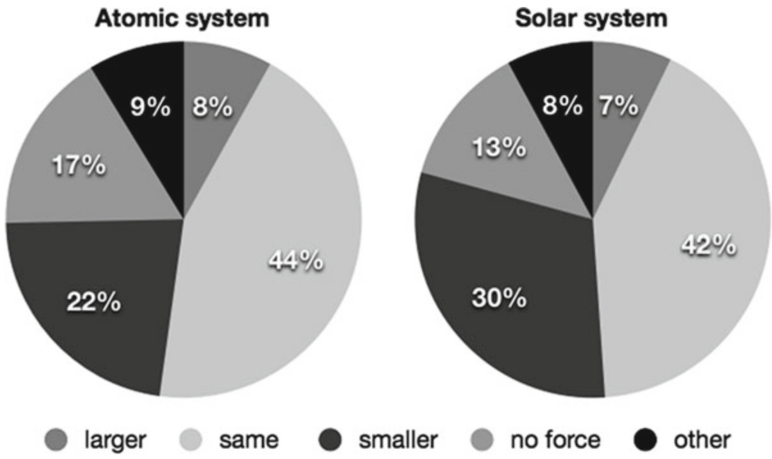


Fig. 6 Student responses regarding the magnitude of the force acting on the central body (nucleus, sun) due to the orbiting body (electron, planet), compared with the force acting on the orbiting body

of the students in the Turkish sample who thought that the force on the central body of an atomic or solar system due to the orbiting body would be larger than, the same magnitude as, or smaller than the force on the orbiting body, or that there would only be force acting on the orbiting body. We note that the common way of talking of a force acting on an object (i.e. when focusing on the effect of the force one of the pair of interacting bodies) could seem to imply force is unidirectional.

As can be seen from Fig. 6, for both systems, a little over two-fifths of the sample gave the canonical response (that the force on both bodies was the same): so this was the most popular response in each case, yet most students got these questions wrong. Significant numbers of students thought that the force acting on the central body would be smaller or even non-existent. Although in physics, forces are seen as interactions, for many students forces are seen to 'belong' to a source body and act on another, reflecting a common pattern for making sense of the world in terms of active agents that act on passive ones (Andersson 1986). Similar patterns have been found to be applied by secondary students in making sense of chemical reactions, by seeing one reactant as acting on a more passive reagent (Taber and García Franco 2010).

Newton's third law is commonly misunderstood by students (Taber 1998), and in our present study, we found that many of the students who selected the correct answer to the objective question justified this in terms of equal forces being needed to maintain the equilibrium in the system. This ignores how for two forces to balance and so cancel, they must be acting on *the same* body. The orbiting bodies in these systems are not in equilibrium: the electrical or gravitational attraction provides the centripetal force needed to cause acceleration and maintain orbit.

The final pair of matched questions asked about forces between the electrons in an atomic system or planets in a solar system. As pointed out above, teachers would

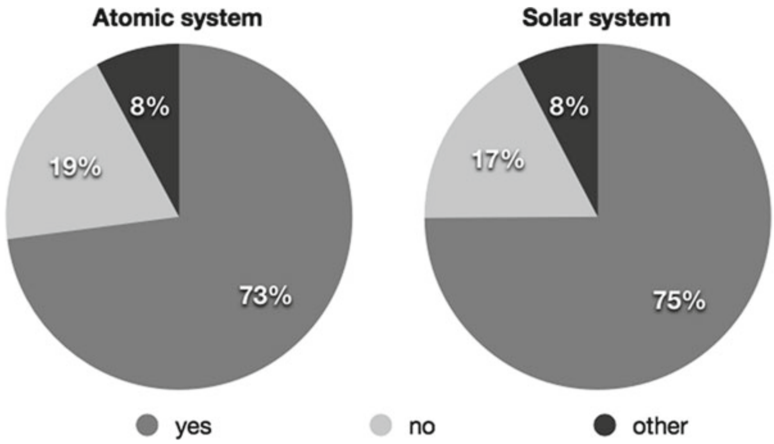


Fig. 7 Student responses on whether there were forces between the orbiting bodies (electrons, planets)

expect secondary student to know that all charged bodies exert an electrical force on each other and that all massive bodies exert a gravitational force on each other. Figure 7 represents the proportions of students who thought there would, or would not, be forces between the orbiting bodies.

As Fig. 7 shows, in each case something like three-quarters of the sample were able to indicate the correct response. This still means that considerable minorities of the sample did not recognise the forces between electrons or between planets. Moreover, as reported above, even where students offered the correct responses, their explanations were often invalid (such as suggesting attractive forces between electrons or repulsive forces between planets).

Conclusion

In this study we asked a sample of upper secondary students in Turkey about the forces acting in two systems – an atomic system and a solar system. Our first research question was: To what extent do Turkish secondary students perceive forces acting in the atomic and solar systems to be analogous? We found that students gave very similar patterns of responses to our questions (see Figs. 4, 5, 6 and 7) in terms of how forces act in the two systems. This would perhaps be less remarkable had responses generally matched canonical knowledge, but we found evidence of widespread alternative conceptions of how forces acted across both systems.

We do not know to what extent students had been exposed to teaching that made explicit use of the 'atom is like a tiny solar system' analogy, and so we do not suggest that this close similarity in the perceptions of the two systems was due to analogical transfer (e.g. knowledge of the solar system mapped onto learning about the atom). Indeed, it seems quite possible that the way both of these systems are understood by learners may be influenced by some intuitive knowledge element which channels thinking about these systems (diSessa 1983, 1993; Taber 2012). This is an area which could be explored in future research. However, our work does suggest that Turkish students may well be very open to recognising an analogy between atomic and solar systems if this is presented in class.

Our second research question was: To what extent are alternative conceptions about the forces acting in the atomic and solar systems that have been identified among British students also found among secondary Turkish students? Students generally recognised how the force between two bodies diminishes with distance, but other responses give more cause for concern. Most students could not accurately describe the main type of force acting in either system, and most did not appreciate the reciprocal nature of force: as acting with equal magnitude on two interacting bodies. There was evidence of a range of alternative conceptions.

The pattern of responses reported here is somewhat different *in detail* to that reported in the work from the UK context – where, for instance, there was a greater knowledge of the role of gravitation in solar systems, but less recognition of the electrical nature of forces operating in the atomic system (Taber 2012). However, the present study suggests that many of the same learning difficulties and alternative conceptions are found in these two contexts (e.g. not recognising the reciprocal nature of force interactions; suggesting greater force is needed to bind a more distant orbiting object to the central body; considering that forces acting on different bodies can balance to maintain an equilibrium) despite the differences in the curriculum and language of instruction in the two different educational contexts.

Our results suggest that Turkish students generally have a limited understanding of the basic physics operating in these two types of system, reflecting much previous research reporting common alternative conceptions of mechanics (Gilbert and Zylbersztajn 1985; McCloskey 1983; McCloskey et al. 1980; Savinainen and Scott 2002; Watts 1983; Watts and Zylbersztajn 1981).

Our work clearly has limitations. Surveys do not provide the fine grain data of interviews that can give greater insight into student thinking. The instrument, whilst certainly having face validity, was not subject to validity and reliability testing in the Turkish context. One possible area of further research might look to refine the instrument through a process including testing written responses with interviews with a sample of respondents (Treagust 1988).

We did not ask our informants whether they had themselves previously met the common analogy between the atom and the solar system, but our results suggest teachers in Turkey should be very careful about using this comparison as a teaching analogy. Teaching analogies can be helpful when there is a good understanding of the analogue, which can be used to map relationships into an unfamiliar target concept (Bellocchi and Ritchie 2011). Even when these conditions occur, effective teaching with analogies requires the teacher to have a good understanding of aspects of the science, the nature of science and specific pedagogy. That is, the teacher needs to have a good understanding of the specific target concept and analogue, of the type of structural mapping central to the productive use of analogy in science and of the need to both emphasise the positive analogy and to also make explicit to learners which salient negative analogical features are not part of the mapping they are being asked to undertake.

The students in our study often had a poor understanding of the forces acting in the solar system, suggesting that for these learners it would not be a suitable analogue to use in teaching about the planetary model of the atom. Indeed our findings suggest that given the tendency for students to perceive the same alternative conceptions of forces to be operating in both systems, reflecting the widely reported difficulty learners face in accepting Newtonian principles of mechanics, the explicit use of this teaching analogy in the Turkish secondary context is most likely to reinforce existing tendencies to develop alternative conceptions.

Acknowledgement The authors thank the teachers in the schools for their support in administering the instrument and acknowledge the Royal Society of Chemistry for funding the Teacher Fellowship project during which the original instrument was developed.

Appendix: The Diagnostic Instrument (in English)

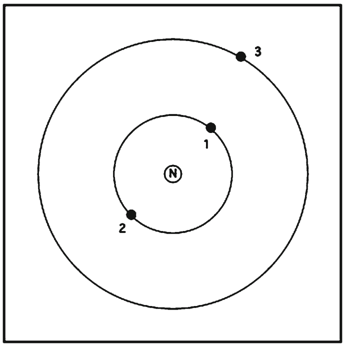
The atom and the solar system

The diagram on the right shows a simple model of an atom.

N is the nucleus, and there are three electrons, labelled 1, 2 and 3.

The electrons are attracted to the nucleus.

Below are some questions about the atom shown in the diagram.



1. What *type of force* attracts the electrons towards the nucleus?	

2. Is **electron 3** attracted to the nucleus by a *stronger* force, a *weaker* force, or the *same size* force as **electron 1?**	

Why do you think this?	

3. Which statement do you think is correct (☑) ?:

☐	the force attracting the nucleus to electron 2 is *larger* than the force attracting electron 2 to the nucleus.
☐	the force attracting the nucleus to electron 2 is the *same size* as the force attracting electron 2 to the nucleus.
☐	the force attracting the nucleus to electron 2 is the *smaller* than the force attracting electron 2 to the nucleus.
☐	there is *no force* acting on the nucleus attracting it to **electron 2.**

Why do you think this?	

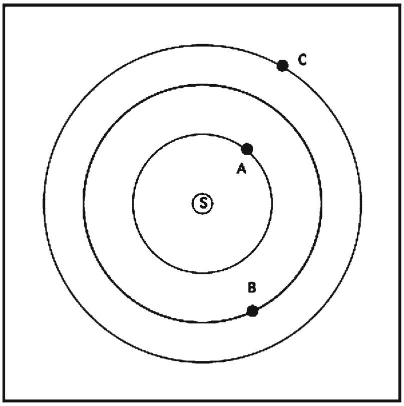
4. Is there any force between **electron 1 and electron 3?**	

Why do you think this?	

(continued)

(continued)

The atom and the solar system



The diagram on the left shows a simple model of a solar system.
S is the sun, and there are three planets, labelled A, B and C.
The planets are attracted to the sun.
Below are some questions about the solar system shown in the diagram.

5. What *type of force* attracts the planets towards the sun?	
6. Is **planet C** attracted to the sun by a *stronger* force, a *weaker* force, or the *same size* force as **planet A?**	

Why do you think this?	

7. Which statement do you think is correct (☑) ?:

☐	the force attracting the sun to planet B is *larger* than the force attracting planet B to the sun
☐	the force attracting the sun to planet B is the *same size* as the force attracting planet B to the sun
☐	the force attracting the sun to planet B is the *smaller* than the force attracting planet B to the sun
☐	there is *no force* acting on the sun attracting it to planet B

Why do you think this?	

8. Is there any force between **planet A** and **planet C?**	

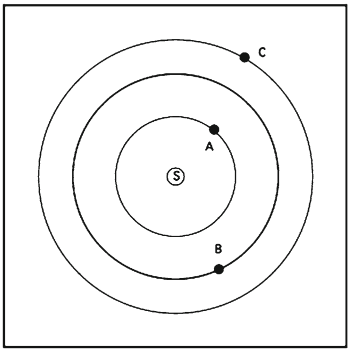
Why do you think this?	

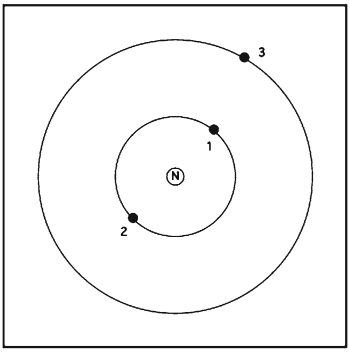
(continued)

(continued)

Comparing the atom with the solar system

Look at the diagrams, and try to think of ways in which the atom and the solar system are *similar*, and ways in which they are *different.*





List the similarities and differences you can think of:

In which ways are they similar?

In which ways are they different?

References

Andersson, B. (1986). The experiential gestalt of causation: A common core to pupils' preconceptions in science. *European Journal of Science Education, 8*(2), 155–171.
Aubusson, P. J., Harrison, A. G., & Ritchie, S. M. (Eds.). (2006). *Metaphor and analogy in science education*. Dordrecht: Springer.
Ausubel, D. P. (2000). *The acquisition and retention of knowledge: A cognitive view*. Dordrecht: Kluwer Academic.
Bearman, C. R., Ball, L. J., & Ormerod, T. C. (2007). The structure and function of spontaneous analogising in domain-based problem solving. *Thinking & Reasoning, 13*(3), 273–294.
Bellocchi, A., & Ritchie, S. M. (2011). Investigating and theorizing discourse during analogy writing in chemistry. *Journal of Research in Science Teaching, 48*(7), 771–792.
Biddle, B. J., & Anderson, D. S. (1986). Theory, methods, knowledge and research on teaching. In M. C. Wittrock (Ed.), *Handbook of research on teaching* (3rd ed., pp. 230–252). New York: Macmillan.
Bodner, G. M. (1986). Constructivism: A theory of knowledge. *Journal of Chemical Education, 63*(10), 873–878.
Brewer, W. F. (2008). Naïve theories of observational astronomy: Review, analysis, and theoretical implications. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 155–204). New York: Routledge.
Coll, R. K. (2008). Effective chemistry analogies. In A. G. Harrison & R. K. Coll (Eds.), *Using analogies in middle and secondary science classrooms* (pp. 132–174). Thousand Oaks: Corwin Press.
diSessa, A. A. (1983). Phenomenology and the evolution of intuition. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 15–33). Hillsdale: Lawrence Erlbaum.
diSessa, A. A. (1993). Towards an epistemology of physics. *Cognition and Instruction, 10*(2&3), 105–225.
Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science, 7*, 155–170.
Gilbert, J. K., & Osborne, R. J. (1980). The use of models in science and science teaching. *European Journal of Science Education, 2*(1), 3–13.
Gilbert, J. K., & Zylbersztajn, A. (1985). A conceptual framework for science education: The case study of force and movement. *European Journal of Science Education, 7*(2), 107–120.
Glasersfeld, E. V. (1989). Cognition, construction of knowledge, and teaching. *Synthese, 80*(1), 121–140.
Glynn, S. M. (1991). Explaining science concepts: A teaching-with-analogies model. In S. M. Glynn, R. H. Yeany, & B. K. Britton (Eds.), *The psychology of learning science* (pp. 219–240). Hillsdale: Lawrence Erlbaum.
Marcelos, M., & Nagem, R. (2010). Comparative structural models of similarities and differences between *vehicle* and *target* in order to teach darwinian *evolution*. *Science & Education, 19*(6), 599–623.
Marcelos, M., & Nagem, R. (2012). Use of the 'tree' analogy in evolution teaching by biology teachers. *Science & Education, 21*(4), 507–541.
McCloskey, M. (1983). Intuitive physics. *Scientific American, 248*(4), 114–122.
McCloskey, M., Carmazza, A., & Green, B. (1980). Curvilinear motion in the absence of external forces: naïve beliefs about the motion of objects. *Science, 210*, 1139–1141.
Mintzes, J. J., Wandersee, J. H., & Novak, J. D. (Eds.). (1998). *Teaching science for understanding: A human constructivist view*. San Diego: Academic.
Muldoon, C. A. (2006). *Shall I compare thee to a pressure wave?: Visualisation, analogy, insight and communication in physics*. Bath: University of Bath.
Nakiboğlu, C. (2008). Using word associations for assessing non major science students' knowledge structure before and after general chemistry instruction: The case of atomic structure. *Chemistry Education Research and Practice, 9*(4), 309–322.

Nakiboğlu, C., & Benlikaya, R. (2001). Misconceptions about orbital concept and modern atom theory (in Turkish). *Kastamonu Egitim Dergisi, 9*(1), 165–174.

Niaz, M., Aguilera, D., Maza, A., & Liendo, G. (2002). Arguments, contradictions, resistances, and conceptual change in students' understanding of atomic structure. *Science Education, 86*(4), 505–525.

Nussbaum, J. (1985). The earth as a cosmic body. In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's ideas in science* (pp. 170–192). Milton Keynes: Open University Press.

Orgill, M., & Bodner, G. M. (2006). An analysis of the effectiveness of analogy use in college-level biochemistry textbooks. *Journal of Research in Science Teaching, 43*(10), 1040–1060.

Osgood, C. E. (1960). Cognitive dynamics in the conduct of human affairs. *The Public Opinion Quarterly, 24*(2), 341–365.

Podolefsky, N. S., & Finkelstein, N. D. (2006). Use of analogy in learning physics: The role of representations. *Physical Review Special Topics – Physics Education Research, 2*(2), 020101.

Sarantopoulos, P., & Tsaparlis, G. (2004). Analogies in chemistry teaching as a means of attainment of cognitive and affective objectives: A longitudinal study in a naturalistic setting, using analogies with a strong social content. *Chemistry Education Research and Practice, 5*(1), 33–50.

Savinainen, A., & Scott, P. (2002). The force concept inventory: A tool for monitoring student learning. *Physics Education, 37*(1), 45–52.

Schraw, G., Wadkins, T., & Olafson, L. (2007). Doing the things we do: A grounded theory of academic procrastination. *Journal of Educational Psychology, 99*(1), 12–25.

Schuman, H., & Presser, S. (1979). The open and closed question. *American Sociological Review, 44*(5), 692–712.

Smardon, R. (2009). Sociocultural and cultural-historical frameworks for science education. In W.-M. Roth & K. Tobin (Eds.), *The world of science education: Handbook of research in North America* (pp. 15–25). Rotterdam: Sense.

Styles, B. (2003). Analogy – constructive or confusing? A students' perspective. *School Science Review, 85*(310), 107–116.

Taber, K. S. (1998). The sharing-out of nuclear attraction: Or I can't think about physics in chemistry. *International Journal of Science Education, 20*(8), 1001–1014.

Taber, K. S. (2001). When the analogy breaks down: Modelling the atom on the solar system. *Physics Education, 36*(3), 222–226.

Taber, K. S. (2002a). *Chemical misconceptions – Prevention, diagnosis and cure: Classroom resources* (Vol. 2). London: Royal Society of Chemistry.

Taber, K. S. (2002b). *Chemical misconceptions – Prevention, diagnosis and cure: Theoretical background* (Vol. 1). London: Royal Society of Chemistry.

Taber, K. S. (2003). The atom in the chemistry curriculum: Fundamental concept, teaching model or epistemological obstacle? *Foundations of Chemistry, 5*(1), 43–84.

Taber, K. S. (2005a). Learning quanta: Barriers to stimulating transitions in student understanding of orbital ideas. *Science Education, 89*(1), 94–116.

Taber, K. S. (2005b). Mind your language: Metaphor can be a double-edged sword. *Physics Education, 40*(11), 11–12.

Taber, K. S. (2008). Exploring student learning from a constructivist perspective in diverse educational contexts. *Journal of Turkish Science Education, 5*(1), 2–21.

Taber, K. S. (2009). *Progressing science education: Constructing the scientific research programme into the contingent nature of learning science*. Dordrecht: Springer.

Taber, K. S. (2010). Straw men and false dichotomies: Overcoming philosophical confusion in chemical education. *Journal of Chemical Education, 87*(5), 552–558.

Taber, K. S. (2012). Upper secondary students' understanding of the basic physical interactions in analogous atomic and solar systems. *Research in Science Education*, 1–30. doi: 10.007/s11165-012-9312-3.

Taber, K. S. (forthcoming). *Modelling learners and learning in science education: Developing representations of concepts, conceptual structure and conceptual change to inform teaching and research*. Springer.

Taber, K. S., & García Franco, A. (2010). Learning processes in chemistry: Drawing upon cognitive resources to learn about the particulate structure of matter. *Journal of the Learning Sciences, 19*(1), 99–142.

Thagard, P. (1992). Analogy, explanation, and education. *Journal of Research in Science Teaching, 29*(6), 537–544.

Tobias, S., Kirschner, P. A., Rosenshine, B. V., Jonassen, D. H., & Spiro, R. J. (2007, April 10). *Debate: Constructivism, discovery, problem-based, experiential, and inquiry-based teaching – Success or failure?* Paper presented at the American Educational Research Association, Chicago.

Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education, 10*(2), 159–169.

Treagust, D. F., Stocklmayer, S., Harrison, A., Venville, G., & Thiele, R. (1994). Observations from the classroom: When analogies go wrong! *Research in Science Education, 24*(1), 380–381.

Tsaparlis, G. (1997). Atomic orbitals, molecular orbitals and related concepts: Conceptual difficulties among chemistry students. *Research in Science Education, 27*(2), 271–287.

Tsaparlis, G., & Papaphotis, G. (2002). Quantum-chemical concepts: Are they suitable for secodnary students? *Chemistry Education Research & Practice, 3*(2), 129–144.

Watts, M. (1983). A study of schoolchildren's alternative frameworks of the concept of force. *European Journal of Science Education, 5*(2), 217–230.

Watts, M., & Zylbersztajn, A. (1981). A survey of some children's ideas about force. *Physics Education, 16*(6), 360–365.

A Study on the Exploratory Use of Microscopic Models as Investigative Tools: The Case of Electrostatic Polarization

Eleni Petridou, Dimitris Psillos, Euripides Hatzikraniotis, and Maria Kallery

Theoretical Background

The significant role of models and modeling in science education has been touted by many researchers (Hestenes 1997; Justi and Van Driel 2005). A model is a set of representations, rules, and reasoning structures that allow one to generate predictions and explanations (Schwarz and White 2005). Models, in this sense of the term, are tools for expressing scientific theories in a form that can be used for purposes such as prediction and explanation. According to Justi and Gilbert (2003), a model:

- Is a non-unique partial representation of an object, an event, a process, or an idea that can be changed
- Is used for enhancing visualization, as a way of both supporting creativity and favoring understanding
- Is used in making predictions about behavior or properties
- Is accredited by competent groups in society

In teaching, models are powerful tools, which may contribute both to students' cognitive evolution and to effective learning (Saari and Viiri 2003). Moreover, models come to play a leading role in inquiry in teaching, since they support an active role for students, who are familiarized with important aspects of scientific methodology. Models can be used for teaching scientific content or aspects of the nature of models and their characteristics (Crawford and Cullin 2004; Lehrer and Schauble 2000). However, in a traditional conservative teaching framework, students use models without understanding that these are tools that can help them predict and explain the phenomena, because typically there is no classroom discussion of their function (Grosslight et al. 1991).

E. Petridou (✉) • D. Psillos • M. Kallery
Department of Primary Education, Aristotle University of Thessaloniki, Thessaloniki, Greece
e-mail: epet@eled.auth.gr

E. Hatzikraniotis
Physics Department, Aristotle University of Thessaloniki, Thessaloniki, Greece

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_9,

Research emphasizes that teachers' knowledge of the nature of models and their fundamental characteristics is limited, and that the predictive function of models is the least understood (Crawford and Cullin 2004; Treagust et al. 2002). Recent studies suggest that students' epistemological awareness of the nature and purpose of models is improved through their involvement in modeling practices that are related to the use of models in science (Petridou et al. 2009a; Windschitl and Thompson 2006). There is, thus, a growing interest in developing and applying innovative approaches aiming at facilitating teachers' use of models and application of modeling procedures in their classes (Crawford and Cullin 2004; Justi and Van Driel 2005; Stylianidou et al. 2003).

Metacognitive procedures, like reflection during exploratory modeling activities, could result in an enhancement in awareness about the nature and purpose of models and modeling. The metacognitive awareness about the nature and purpose of models, in general, enables students to have choice and some degree of control over what they do and how they do it, and so they are more likely to benefit from them (Aiello-Nicosia and Sperandeo-Mineo 2000). Prompting students to reflect has been found to help students acquire awareness of their cognitive repertoires, and so it may lead to better learning results and greater understanding of the subject matter and the inquiry process (White and Frederiksen 1998). Moreover, Schwarz and White (2005) argue that without metacognitive awareness, students cannot fully understand the nature of science, and their ability to use and develop scientific models will be hampered. In our research, reflection was used during a metacognitive phase, in order to enhance students' metacognitive awareness about the exploratory use of models in the educational unit.

Mellar and Bliss (1994) distinguish modeling activities as exploratory or expressive. In exploratory activities, students interact with prepared models, while in expressive procedures, students engage in the construction of models. Expressive procedures are often used particularly with the use of ICT (information and communication technology) tools. When the learner is involved directly in model construction, there is a possibility of disorientation from the substantial use of models as investigative tools (Sins et al. 2005). Furthermore, Crawford and Cullin (2004) asked prospective secondary science teachers to participate actively in a model-based teaching experiment comprising two phases. In phase I, the prospective teachers designed an open-ended investigation of a plant, water, and soil system. In phase II, the teachers constructed a computer model of their particular system using the Model-It dynamic modeling software. In their findings, they report that the prospective science teachers were much more focused on how to identify variables and create appropriate relationships as a result of their experience with building and testing models using Model-It, but that their understanding of how scientists use models actually changed very little.

Whatever the kind of the modeling procedures applied, models in instruction can be used for explaining a phenomenon or for predicting it. Models in instruction are used mainly in an explanatory, not a predictive, way. So, students first observe the phenomenon and afterward, with the help of the model, try to explain it. For example, the explanatory function of models is underpinned by an interesting process, proposed by Otero et al. (1999), of making a concept prediction, performing a computer experiment, and obtaining concept evidence. Specifically, the prospective teachers that participated in the model-based unit with model-like observations were able to check their explanatory models in order to explain their observations of the hands-on experiment. On the other side, there are some researchers focusing on the predictive use of models that reveal interesting students' difficulties. Treagust et al. (2004) show that secondary students do not recognize the predictive nature of models, despite using them in a predictive fashion in their chemistry class.

The necessity of models in instruction is particularly evident when the interpretation of the phenomenon studied is not readily apparent, and submicroscopic models provide the basis for a causal account of phenomena at study. Electrostatic phenomena are a representative example, because interpreting them requires submicroscopic models. Furthermore, electrostatics is a fundamental area of physics that is connected with everyday life. Research has shown that students and prospective teachers face difficulties in interpreting electrostatic phenomena (Barbas and Psillos 2003; Furio et al. 2004; Harrington 1999). For example, Harrington (1999) asked 162 prospective teachers about the interaction between an uncharged and a charged body and found that less than 28 % of them gave scientifically acceptable answers. Ignorance of the attraction between a charged and an uncharged body in students aged 18–21 was also mentioned by Furio et al. (2004). Barbas and Psillos (2003) investigated the explanation of the attraction between an uncharged and a charged body and found that the majority of prospective teachers assigned the attraction to the charged body without referring to the polarization of the uncharged body.

In Greece a new curriculum for compulsory education (6–15 years) is under development. One of the objectives of the New Greek National Curriculum for science education is to change the "transmission model" of instruction to more student-centered instructional approaches. The aim is to acquaint students with the scientific way of thinking and aspects of the nature of science. More specifically with regard to models, the curriculum mentions: "Students will also be expected to build and use scientific models in order to describe, explain and predict some physical or chemical phenomena and processes." Submicroscopic models are usually introduced to students toward the end of primary education. Thus, the use of scientific models by the students supports this aim as models can give students the opportunity to come closer to scientific methodology and exploratory procedures.

In this context we designed and implemented an educational unit in order to help students to overcome the difficulties related to their understanding of the predictive function of models. The unit focused on the active, exploratory use of a submicroscopic model as a predictive tool. Additionally, students reflected on those features of the model in order to understand its use as an investigative tool.

The aims of the present research were to:

- Investigate whether lower secondary students and student teachers are able to use the submicroscopic model of electrostatic polarization in order to predict the attraction between charged and uncharged balloons (phenomenon)
- Investigate whether the students gain awareness of the use of models as an investigative tool
- Investigate which features of the model helped students to predict the phenomenon

Research Method

The Context

Two samples, one consisting of 12 primary education student teachers and a second of 12 lower secondary education students, were used in this study. They both attended the three-hour model-based instructional unit described below. It should be noted that the Greek general secondary education includes a 3-year lower secondary education called gymnasium and a 3-year upper secondary school called lyceum. Primary education and gymnasium are compulsory for all students. At the time of the project, the participating secondary school students were approaching the end of their second year of their high school studies. The students of our study were introduced to elementary electrostatics in primary school 3 years before the start of the project having some experiences with electrostatic experiments like, for example, the attraction of paper by a plastic pen rubbed with a woolen cloth.

In Greece the students who finish secondary education can enter university after taking the national entrance examinations in which they are examined in different subjects depending on the subject of their university studies. Specifically the primary education candidates are examined in courses related to history, literature, and language, and they usually have a weak background knowledge in science. The student teachers who participated in our study attended the compulsory course of the "Didactics of Science" in the Department of Primary Education at the Aristotle University of Thessaloniki.

Both high school students and student teachers worked in small groups in front of personal computers following specially developed worksheets that guided and prompted them to use the model as an investigative tool. Both samples dealt with the same submicroscopic model of electrostatic polarization, as their level of understanding about electrostatic polarization was more or less similar, according to a pilot study. This was corroborated by results of the present study as shown in the section "Results." The language used in the tasks was adapted appropriately for the school students. The unit was implemented with the student teachers in a computer-equipped university classroom in Thessaloniki, Greece, in the context of a science course while with the lower secondary students in a computer-equipped classroom of their school in a rural city of Northern Greece.

The Model-Based Educational Unit

The Structure of the Educational Unit

The focus of the educational unit is for both the student teachers and lower secondary students to use and to be aware of the model as an investigative tool and be capable to account for the predictive use of models. Specifically, both groups of students initially predicted what would happen between a charged and an uncharged balloon

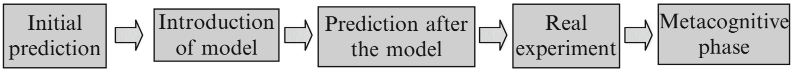


Fig. 1 Structure of the unit

that were attached to strings from the ceiling. They were then introduced to the model of polarization and asked to indicate their predictions of the same phenomenon again, before the actual experiment with balloons was performed. After the experiment, the students took part in a metacognitive phase that helped them become conscious of the way they utilized the model. Figure 1 shows the structure of each unit.

What we have done here is to extend the well-known predict–observe–explain structure proposed by White and Gunstone (1992) and adapt it to the teaching of the concept of models, particularly their predictive function. By inserting the introduction of the model and a second prediction of the phenomenon between the prediction and observation phases, we prompt students to use the model as an investigative tool for predicting the phenomenon. The real experiment that always follows the introduction of the model comes to play a confirming role of what actually happens in the phenomenon, while the metacognitive phase at the end plays the significant role of stimulating awareness of the whole procedure.

The Phenomenon Studied

We consider the attraction between a charged and an uncharged balloon to be an appropriate phenomenon for teaching models because (a) it comes from classroom experience, (b) the experiment is easy to carry out, (c) neither lower secondary students nor student teachers know it before working with the model, and (d) a submicroscopic model (polarization) is necessary in order to study it.

The Model of Electric Polarization

The model of polarization consists of a sequence of three simulated representations, the atom, the dipole, and the insulator, where the user can see the behavior of an atom and the forces exerted on a dipole and an insulator when an external charge is placed anywhere near them. According to this model [more information is provided in Petridou et al. (2009a)] the user can move an external charge anywhere close to the atom and watch the deformation of the electronic cloud from spherical symmetry toward or away from the external charge, attracted or repelled it depending on the polarity of the charge (Fig. 2a). Next, when the user moves a negative external charge close to the dipole, the positive charge of the dipole comes close to the external charge as it is attracted to it, while the negative charge of the dipole is moving away as it is repelled from it. In this case, the attractive force is bigger than the repulsive one, as the distance of the opposite charge of the dipole from the external charge is less than the distance of the same charge (Fig. 2b). In the third representation that

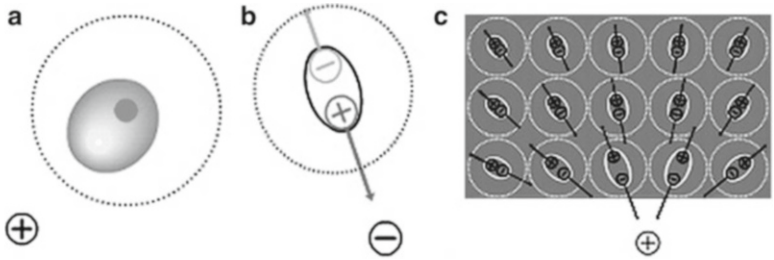


Fig. 2 The model of polarization. (**a**) The atom, (**b**) the dipole, and (**c**) the insulator

represents a part of an insulator, both the attractive and repulsive forces exerted to each dipole are indicated in order that the students can compare them and to conclude that, as in representation 2, for each dipole, the total force is attractive; also in the whole body, the total force is attractive too (Fig. 2c). The first representation is the atom with its known constituents, from which is constructed the concept of the dipole and an appropriate means of representing the forces of attraction and repulsion exerted. The sequence of the three representations (atom, dipole, and insulator) of the model of polarization, as shown in Fig. 2, provides a smooth passage from the submicroscopic to the macroscopic level.

In the course of the unit, the students were guided to be engaged in specific tasks embedded in worksheets involving the use of the model such as polarization of single atom, appearing of forces, and qualitative recognition of the mutual attraction between the uncharged and the charged balloon, though without specific treatment of Newton's Third law. The computer-simulated submicroscopic model of polarization is considered to be appropriate for enhancing an understanding of the model as an investigative tool because it provides a means for visualizing the underlying causal mechanism, which is not observable. It is also simple to handle and facilitates the cognitive bridging of the submicroscopic mechanism with the phenomenon as well as reflection on its features and function, which helps students to predict the phenomenon.

Research Instruments

Before and after the exploration of the model of polarization, the students were asked to predict the same phenomenon in a multiple-level task, which included an open and a closed question. Specifically, we asked students to predict, in part a of the task, what will happen between two balloons that are free to move, if the one is negatively charged and the other is uncharged with both attached to strings which hang from the ceiling close to each other. Content validity of the tasks was verified by two experienced physics researchers and two science education professors. After students answered this question, in part b of the task, we then asked them to choose one or more possible images showing different interactions between the two

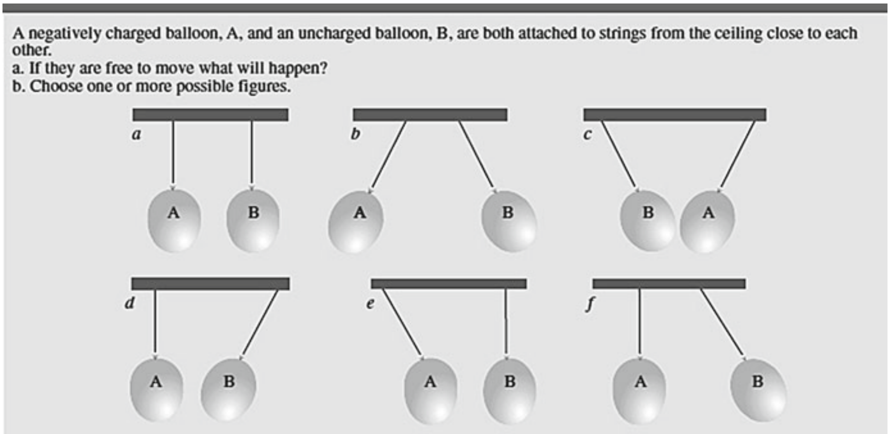


Fig. 3 Pre- and post-worksheet task

balloons as shown in Fig. 3 (Petridou et al. 2009a). The multiple choice part b of the task was given in order to avoid a lack of response and to help students think about the phenomenon.

Data were obtained by analysis of the student teacher's pre–post written predictions on the task and of tape-recorded in-depth group interviews. The group interviews, which corroborate the freely expressed ideas (Vaughn et al. 1996), were based on the students' written answers and helped in eliciting the students' ideas in depth (Cohen and Manion 1989) and in their understanding of each other's ideas. In university, each of the three groups consisting of four student teachers was interviewed separately. The lower secondary students were interviewed together in their classroom as the time limit of each class session did not allow smaller group assessments. Data were obtained by analysis of the videotaped discussion. The questions addressed by the researcher were based on the task questions and stimulated students to justify in detail their written answers and their selections with balloons' images. So, the interview began with the presentation of the students' written answers and continued with discussing, as analytically as possible, the justification of the written answers. In this way it was ensured that all different ideas were expressed. The role of the researcher in both cases was to lead and coordinate.

Research data for the investigation of students' awareness of the model as an investigative tool, and for the selection of those elements that helped them to predict the phenomenon, were obtained by an analysis of their written answers and the transcribed interviews that were based on students' written answers to the metacognitive phase. Specifically, both experimental groups of students were asked to answer two metacognitive questions. Initially, to say *what they used the model for*, this prompted them to reflect on how they had utilized the task with the model during the unit. Similarly, in the second task, they were asked to *describe the elements of the model that helped them to predict the specific phenomenon*, in order to elicit the different aspects that helped them to do this. The analysis and categorization of students' written and interview answers was carried out by two researchers who interacted continuously to classify the students' responses. Specifically, answers to the first question were categorized in three levels: those that referred to the predictive use of models, those that referred only to explanatory use of models, and those that did not recognize any of these functions. Answers to the second question were categorized according to the elements of the simulated model that students referred to. These raters marked independently a selected number of answers after coming to an agreement about the characteristics of each category. Cases of disagreement between their ratings were resolved by discussion. A high level of inter-rater reliability (0.82) was achieved in the final scoring.

Results

Initial Predictions of the Phenomenon

Before the introduction to the model, both groups of students (lower secondary and student teachers) gave varied wrong predictions, such as that there is no interaction between the uncharged and the charged balloons, that there is repulsion between the balloons, or that the charged balloon attracts the uncharged one (a one-way attraction).

No Interaction

Seven of the twelve lower secondary students and 10 of the 12 student teachers predicted no interaction between the uncharged and the charged balloons. A typical prediction was: "An uncharged body does not interact with either the positive or the negative charges since it is neutral. Thus, the balloons will stay still" (lower secondary student).

Repulsion

Four of the twelve lower secondary students and 1 of the 12 student teachers predicted repulsion between the uncharged and the charged balloons. A typical prediction was: "One balloon will repel the other since balloon A is negatively charged. If balloon A was positively charged it would push it away again since this time it would repel the positively charged particles of B" (lower secondary student).

Attraction and/or Repulsion

One student teacher predicted that there could be both repulsion and attraction between the uncharged and the charged balloons, and one lower secondary student predicted the one-way attraction, that the charged balloon attracts the uncharged one, and not the mutual attraction between the balloons.

Predictions of the Same Phenomenon After the Elaboration with the Model

After the introduction of the model, the majority of the students in both groups gave the correct prediction that the two balloons are attracted to each other.

Mutual Attraction

Ten of the twelve lower secondary students and 8 of the 12 student teachers correctly predicted the mutual attraction between the two balloons. Typical predictions were: "The two balloons are attracted to each other since we saw that when an external charge, positive or negative, approaches an uncharged body, then the positive and the negative charges of the neutrally charged body separate and if for example the external charge is positive then attracts the negative part and repels the positive and vise versa. So two forces appear, the attractive and the repulsive, of which the attractive is greater" (student teacher*)* and "the electrons of the balloon A attracts the positive charge of the balloon B and so the two balloons are coming close to each other" (school student).

Attraction

Two of the twelve lower secondary students and 2 of the 12 student teachers predicted that the charged balloon attracts the uncharged one.

No Interaction

One student teacher predicted after the introduction of the model that there is no interaction between the two balloons.

Repulsion

One student teacher predicted repulsion between the uncharged and the charged balloons.

The cumulative pre- and post-predictions are presented in Table 1.

It seems that while, prior to introduction of the model, the majority of the students (either student teachers or lower secondary students) predicted that there would be no interaction between the balloons, there is an important change in their opinions after the model since the majority of the students in both samples mentioned not only the interaction between the balloons but also the mutual attraction between them. This was in line with the aims of the unit following students' engagement with the model and the worksheet tasks.

Table 1 Pre- and post-predictions on worksheet task

Balloons' interactions	Predictions			
	Pre		Post	
	Lower secondary students	Student teachers	Lower secondary students	Student teachers
No interaction between the balloons (*a*)	7/12	10/12	0/12	1/12
Repulsion between the balloons (*b*)	4/12	1/12	0/12	1/12
Attraction and repulsion (*b and c*)	0/12	1/12	0/12	0/12
The charged balloon attracts the uncharged (*d*)	1/12	0/12	2/12	2/12
Mutual attraction (*c*)	0/12	0/12	10/12	8/12

Metacognitive Phase

In the metacognitive phase, when students were prompted to reflect on the way they had incorporated the task with the model during the unit, the majority of the student teachers (10/12) and half of the lower secondary students (6/12) showed that they had understood the *predictive function* of the model and stated it directly or indirectly: "I used the model in order to predict the attraction between a charged and an uncharged balloon. In the experiment we can see only the effect while with the model we can predict and explain what is happening" (student teacher) or "I have used the model for understanding what happens with the charges, something that is not possible to see in detail in reality at the level of atom and thus to be able to predict what will happen to the balloons" (student teacher) or "we have used the model to understand what happens with the atoms and to be able to say what will happen in the experiment" (lower secondary student). It should be noted here that all students answered in Greek and that there was an exact translation of their answers to English.

Two student teachers and two lower secondary students talked only about the explanatory function of the model: "I have used the model to understand the phenomenon" (student teacher) or "I have used the model to be able to explain the experiment correctly and with proof" (lower secondary student).

Four lower secondary students seem to *confuse the model with the experiment*: "with the model I was able to see if my prediction was right or wrong. We finally saw what happens."

These results are compiled in Table 2.

In the second question of the metacognitive phase, students were prompted to identify the different elements of the model that helped them predict the phenomenon. Based on their responses, we may conclude that the elements of the simulated model of polarization that helped each student were different.

As shown in Table 3, four student teachers and two lower secondary students referred to the shifting of the electronic cloud of the atom: "I discern the shifting of the electronic cloud and its changing of shape" (student teacher).

Four student teachers and six lower secondary students referred to the formation of the dipole and the attractive and repulsive forces exerted on its poles when the

Table 2 Understanding model use

	Student teachers	Lower secondary students
Prediction	10/12	6/12
Explanation	2/12	2/12
Confusion between model and experiment		4/12

external charge was moved near them: “the dipole helped me a lot because I understood better the separation of positive and negative charges when these are close to a charged body” (lower secondary student) or “I was helped by the fact that I could see simultaneously on the dipole the attractive and the repulsive force” (student teacher) or “I liked the fact that we could move the external charge anywhere we wanted and we were watching the movement of all the dipoles in the insulator” (lower secondary student).

Four student teachers and two lower secondary students mentioned that the representation of the insulator formed a bridge between the submicroscopic and the macroscopic level: “when I was watching the insulator I was thinking about the balloon, it helped me to make the connection between the microscopic and the macroscopic level” (student teacher).

Finally, two student teachers referred to the whole sequence of the atom, the dipole, and the insulator and the representation of the dependence between the distance and the forces exerted: “at the beginning we saw the deformation of the electronic cloud, then we saw the dipole and at the end we saw all the dipoles inside the insulator. All this sequence helped me…I think that only with the one representation I couldn’t predict the phenomenon.”

We have not included the answers of two lower secondary students who mentioned that they prefer the experiment with the two balloons on the table. It was not a surprise for us as these same students confused the model with the experiment in the first question of the metacognitive phase.

Discussion and Concluding Remarks

The focus of the present study was (a) to investigate whether lower secondary students and student teachers are able to use the microscopic model of polarization in order to predict the mutual attraction between charged and uncharged balloons (phenomenon), (b) to investigate whether these students gain awareness of the use of the model as an investigative tool, and (c) to investigate which features of the model helped students to predict the phenomenon.

Regarding the capability of using the model as an investigative tool, the results show that there was progress in both groups in predicting the mutual attraction between the two balloons after their introduction to the microscopic model of polarization. We consider that the specific structure of the unit, in which we ask students

Table 3 Elements of the model cited by students

Features of polarization	Visualization on model	Number of students that referred
Atom	Deformation of electronic cloud on atom	*4/12* student teachers *2/12* lower secondary
Dipole	Formation of dipole and attractive and repulsive forces on dipoles	*4/12* student teachers *6/12* lower secondary
Insulator	Many dipoles in a part of an insulator	*4/12* student teachers *2/12* lower secondary
Sequence: atom–dipole–insulator	Possibility of moving the external charge anywhere near the atom, dipole, or insulator and representation of the dependence between the distance and the forces	*2/12* student teachers

to predict the same phenomenon twice, before and after the introduction of the model, prompts students to use the model as an investigative tool. We can say that students are "forced" to use the elements of the model in order to predict the phenomenon.

Regarding whether the students became conscious of how they used the model, the results show that some students had used the model as an investigative tool and predicted the phenomenon with its help but without realizing it. These data support the claim (a) that the use of models as an investigative tool in exploratory activities alone is not enough for understanding the concept of models, and (b) that metacognitive procedures are particular demanding. Specifically, while 10 of the 12 lower secondary students correctly predicted the phenomenon with the help of the model, in replying to the metacognitive question "what did you use the model for," only 6 of the 12 lower secondary students cited the predictive use of the model. With the student teachers, the results are different; eight of the twelve predicted the phenomenon correctly with the use of the model, but ten of them became conscious of the predictive use of models in the metacognitive phase. It is not surprising that this progress is more significant among the student teachers since the awareness of the model as an investigative tool is unquestionably a demanding procedure. That is why 4 of the 12 lower secondary students confused the model with the experiment after their participation with the educational module, while student teachers do not seem to have this problem. These data confirm the crucial role that the metacognitive phase plays in understanding such a difficult concept as the model (Aiello-Nicosia et al. 2000; Schwarz and White 2005). Treagust et al. (2004) discuss in their findings the fact that their students, who had not participated in metacognitive procedures, actively used the teaching models in a predictive way without however realizing it. We consider that the active use of models alone is not adequate for understanding the nature of models, while reflecting on the way in which they used the models can help students to become conscious of this process and to understand the concept of models (Petridou et al. 2009b). So, an important element of the educational unit, for understanding the model as an investigative tool, was students' participation in the metacognitive procedure during which they had the chance to reflect on the way they used the model.

The features of the model that helped students to predict the phenomenon were different for different students. Table 3 shows that student teachers seem to have no preference for one or another of the representations of the atom, the dipole, or the insulator, as the same number of student teachers cited each of the three. However, lower secondary students seem to prefer the representation of the dipole, since half of them mentioned the formation of the dipole or the forces exerted on its poles. Maybe this possible preference to the dipole is due to the "direct" representation of the attractive and repulsive forces that the dipole includes, which is the cause of polarization.

Considering the educational implications, the above results suggest that it is important to include the representation of both attractive and repulsive forces on dipoles in science curricula aiming at students' understanding of electrostatic polarization. It is important for teachers and curricula designers to provide for different representations of a model in order to handle different learning prompts that are appropriate for several students. Moreover, the active use of models as investigative tools combined with metacognitive procedures at the end of instruction seems to help students to rethink of the way they handled a model and to become conscious of the investigative power of this model. Finally, considering the research implications, the present study paves the way for applying similar instruction in a large classroom on the one hand, as the sample of the present study is small, and on the other, to adapt and investigate the same strategy for the predictive use of models in other topics.

References

Aiello-Nicosia, L. M., & Sperandeo-Mineo, M. R. (2000). Educational reconstruction of physics content to be taught and of pre-service teacher training: A case study. *International Journal of Science Education, 22*(10), 1085–1097.

Barbas, A., & Psillos, D. (2003). Evolution of students' reasoning about microscopic processes in electrostatics under the influence of interactive simulations. In D. Psillos (Ed.), *Teaching and learning in the science laboratory* (pp. 243–254). Boston: Kluwer Academic.

Cohen, L., & Manion, L. (1989). *Research methods in education* (3rd ed.). London: Routledge.

Crawford, B. A., & Cullin, M. J. (2004). Supporting prospective teachers' conceptions of modeling in science. *International Journal of Science Education, 26*(11), 1379–1401.

Furio, C., Guisasola, J., & Almudi, M. J. (2004). Elementary electrostatic phenomena: Historical hindrances and students' difficulties. *Canadian Journal of Science, Mathematics, and Technology Education, 4*(3), 291–313.

Grosslight, L., Unger, C., Jay, E., & Smith, C. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*(9), 799–822.

Harrington, R. (1999). Discovering the reasoning behind the words: An example from electrostatics. *American Journal of Physics, 67*(7), 58–59.
Hestenes, D. (1997). Modeling methodology for physics teachers. In E. F. Redish & J. S. Rigden (Eds.), *Proceedings of international conference on undergraduate physics education* (pp. 935–957). New York: The American Institute of Physics.
Justi, R., & Gilbert, J. (2003). Teachers' views on the nature of models. *International Journal of Science Education, 25*, 1369–1386.
Justi, S. R., & Van Driel, J. H. (2005). The development of science teachers' knowledge on models and modelling: Promoting, characterizing and understanding the process. *International Journal of Science Education, 27*, 549–573.
Lehrer, R., & Schauble, L. (2000). Modeling in mathematics and science. In R. Glaser (Ed.), *Advances in instructional psychology* (Vol. 5, pp. 101–159). Mahwah: Erlbaum.
Mellar, H., & Bliss, J. (1994). Introduction: Modelling and education. In H. Mellar, J. Bliss, R. Boohan, J. Ogborn, & C. Tompsett (Eds.), *Learning with artificial worlds: Computer based modelling in the curriculum* (pp. 1–7). London: Falmer Press.
Otero, V., Johnson, A., & Goldberg, F. (1999). How does the computer facilitate the development of physics knowledge among prospective elementary teachers? *Journal of Teacher Education, 181*(2), 57–89.
Petridou, E., Psillos, D., Hatzikraniotis, E., & Viiri, I. (2009a). Design and development of a microscopic model in polarization. *Physics Education, 44*, 589–598.
Petridou, E., Psillos, D., Hatzikraniotis, E., & Viiri, J. (2009b, August–September). *Teaching aspects of models to pre-service primary teachers: The case of polarization*. Paper presented at 7th European Science Education Research Association (ESERA) Conference, Istanbul.
Saari, H., & Viiri, J. (2003). An investigative-based teaching sequence for teaching the concept of modelling to seventh-grade students. *International Journal of Science Education, 25*, 1333–1352.
Schwarz, V. C., & White, Y. B. (2005). Metamodeling knowledge: Developing students' understanding of scientific modeling. *Cognition and Instruction, 23*(2), 165–205.
Sins, H. M. P., Savelsbergh, R. E., & van Joolingen, R. W. (2005). The difficult process of scientific modelling: An analysis of novices' reasoning during computer-based modelling. *International Journal of Science Education, 27*(14), 1695–1721.
Stylianidou, F., Boohan, R., & Ogborn, J. (2003). Computer modelling and simulation in science lessons: Using research into teachers' transformations to inform training. In D. Psillos et al. (Eds.), *Science education research in the knowledge-based society* (pp. 361–369). Dordrecht: Kluwer Academic.
Treagust, F. D., Chittleborough, G., & Mamiala, L. T. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education, 24*, 357–368.
Treagust, F. D., Chittleborough, G., & Mamiala, L. T. (2004). Students' understanding of the descriptive and predictive nature of teaching models in organic chemistry. *Research in Science Education, 34*, 1–20.
Vaughn, S., Schumm, J. S., & Sinagub, J. M. (1996). *Focus group interviews in education and psychology*. London: Sage.
White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction, 16*(1), 3–118.
White, R. T., & Gunstone, R. F. (1992). *Probing understanding*. London: Falmer Press.
Windschitl, M., & Thompson, J. (2006). Transcending simple forms of school science investigation: The impact of preservice instruction on teachers' understandings of model-based inquiry. *American Educational Research Journal, 43*(4), 783–835.

Teacher Pathways Through the Particulate Nature of Matter in Lower Secondary School Chemistry: Continuous Switching Between Different Models or a Coherent Conceptual Structure?

Ingo Eilks

Introduction

Explaining macroscopic phenomena on the submicro level is considered to be one of the essential ideas of modern chemistry and chemistry teaching (Johnstone 1991). Nevertheless, science education research indicates that this task is not easily achieved. A wide variety of conceptual gaps in students' understanding of the particulate level have been identified in the last 30 years, e.g., concerning the concept of matter as such (Krnel et al. 1998), particle interpretations of chemical phenomena (Garnett et al. 1995), chemical reactions (Anderson 1990), or bonding theory (Hofstein et al. 2010).

Several reasons for students' learning difficulties with structural concepts are mentioned in the literature. One source refers to the often unclear relationship of the macroscopic, submicroscopic, and symbolic level of knowledge (Johnstone 1991). But other gaps like unclear distinctions between the levels inside the range of macro to submicro domains (Eilks et al. 2007), the neglect of meso-levels (Meijer et al. 2009), and low levels of understanding about the nature of models and modeling (Grosslight et al. 1991) have also been mentioned as causes of learning difficulties.

This chapter takes into account that the teacher is considered the key factor for any sustainable change in the science classroom (Eilks et al. 2006). The question of analysis of teachers' prevalent practices in teaching about the submicro world and the search for developing better teaching strategies is approached using two different case studies. The first is an explorative study on the beliefs of 28 experienced chemistry teachers, which asks how one should teach the particulate nature of matter via atomic structure to finally arrive at bonding theory (Bindernagel and Eilks 2009). Pathways German chemistry teachers commonly use throughout the entire

I. Eilks (✉)
Institute of Science Education (IDN), University of Bremen, Bremen, Germany
e-mail: ingo.eilks@unibremen.de

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_10,

lower secondary chemistry curriculum (grades 5–10, ages 10–16) will be described. Reflection will take place as to whether or not the most commonly adopted teaching approaches might actually cause lower levels of learning success in dealing with structural concepts. This study will be contrasted with a second research project consisting of over a decade of Participatory Action Research (PAR) (Eilks and Ralle 2002). This project created a different teaching approach, which aims to produce an overarching, coherent structure for the entire lower secondary curriculum when dealing with macro- and submicroscopic concepts in chemistry (e.g., Eilks 2002; Eilks and Moellering 2001; Eilks et al. 2007).

German Teachers' Pathways Through the Particulate Nature of Matter and Their Understanding of Models and Modeling

Research-Oriented Learning in Chemistry Education

Wildt (2006) points out that "research-oriented learning" can have two meanings: (I) research-oriented learning as a form of education based on asking students to work on actual research studies or (II) a special kind of education program which (partly) integrates students learning into ongoing research processes.

In the course model this study stems from, we merge both sides of research-oriented learning in the sense discussed above. Searches of existing literature sources are coupled with personal experience gained in small-scale, individual research projects. We consider the mix of personal involvement with original research papers, plus active, individual data collection and interpretation to provide a fruitful setting, which gives student teachers insights into the objectives, methods, potential, and limitations of science education research (Bindernagel and Eilks 2009; Feierabend et al. 2011).

In the research described here, fourth-year student teachers of chemistry participated in teacher training seminars in their subject. The goal of these seminars was to arrive at research-based lesson plans for lower secondary chemistry lessons. They could freely opt for three different topics: (I) the introduction of a first particle concept, (II) addressing the first concepts of chemical reactions, or (III) introducing basic atomic structure and bonding (Bindernagel and Eilks 2009).

Three major sources of information were presented in a theoretical introduction, which served as resources for the student teachers' lesson planning: empirical research, curriculum development, and classroom practice. We asked the student teachers to combine knowledge from all three domains. They were asked to use relevant outcomes from empirical research, i.e., the large number of papers and reviews available on research studies concerning students' alternative frameworks and learning difficulties. The field of curriculum development also offers a wide variety of sources for structuring lessons, i.e., textbooks or science teachers' journals. Additionally, the student teachers were sensitized to the missing connection between empirical evidence and curriculum materials. They discussed textbook illustrations and Internet resources, which explicitly illustrate commonly known misconceptions and learning difficulties of students (e.g., Eilks 2003; Eilks et al. 2007, 2009). The field of classroom practice is the only aspect that lacks information in written or printed form. In this particular area, the student teachers were asked to create their own research-based resource interviewing experienced teachers.

Method and Sample

Fifty-six student teachers from two academic years participated in the course described above, during which 28 experienced chemistry teachers were interviewed. Each interview was conducted by pairs of student teachers. This approach inspired a friendly atmosphere of discussion, mirroring the situation in which an experienced teacher coaches a younger colleague in the workaday world of school (Bindernagel and Eilks 2009; Feierabend et al. 2011). Teachers were randomly selected from schools where the students had had internships in the year prior to the seminar. Most of the teachers ranged between 40 and 60 years old. Twenty-five of them had more than 5 years of practical experience in chemistry teaching (Bindernagel and Eilks 2009).

An interview guide was provided to the student teachers. It included questions about teaching strategies in each of the three relevant issues (the particulate nature of matter, chemical reactions, atomic structure, and bonding), including queries about personal teaching experiences and the use of specific “submicroscopic” illustrations extracted from textbooks. The interview guide can be viewed in Bindernagel and Eilks (2009). All interviews lasted roughly 45 min and were audio-taped and later transcribed.

During the seminar, analysis of the raw interview data was undertaken. The teacher trainees gave a short presentation on their own interviews, using the topics in the interview guide as a map. In parallel with the seminar, the university researchers began detailed analysis of the data. Key aspects of this analysis were:

- Characterizing the teachers’ curricular approach when dealing with the different submicroscopic concepts over the course of lower secondary school lessons by qualitative content analysis (Mayring 2000), then transferred into a graphic format mapping out the pathways chosen by the teachers (see below).
- Teachers’ understanding of the nature of models and modeling when explaining their personal teaching approach by an evaluation grid (Sprotte and Eilks 2007) inspired by Grosslight et al. (1991).

Findings and Discussion

Figure 1 provides an overview of the teaching pathways used by 28 experienced German chemistry teachers. The boxes in the graph represent the different submicroscopic models (see Table 1) the teachers touched upon in their interviews.

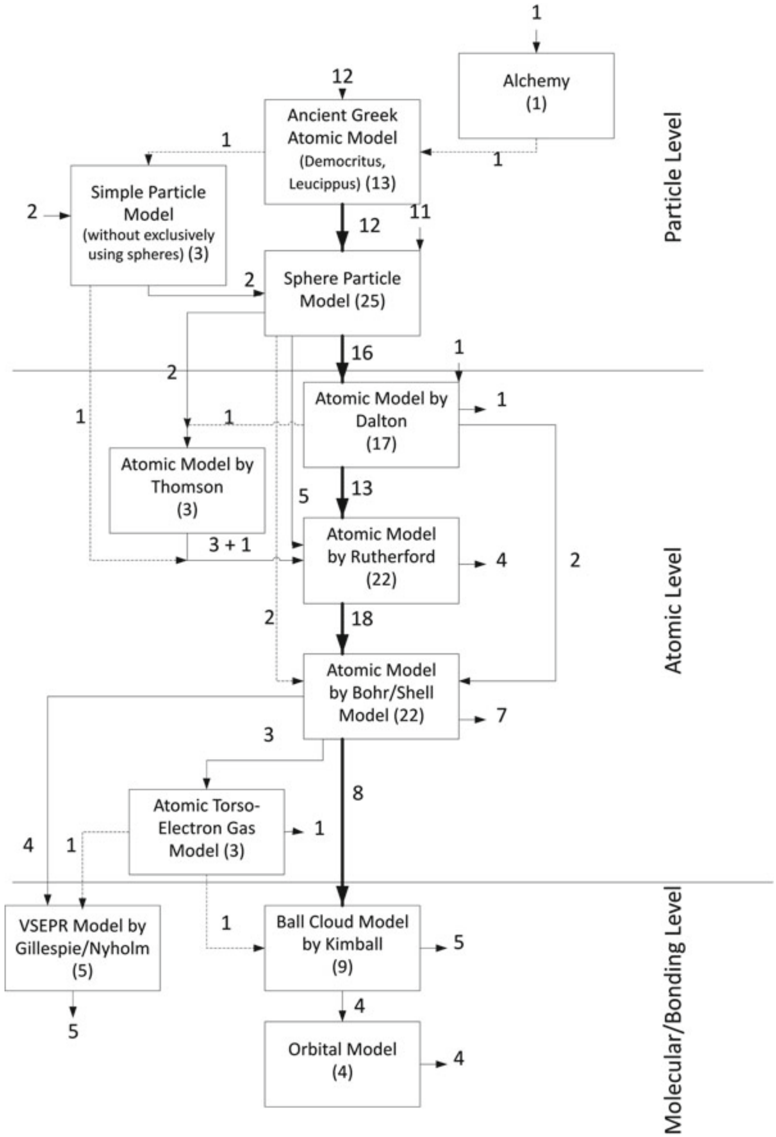


Fig. 1 Teaching pathways for 27 of the 28 teachers. One of the teachers professed that he exclusively used project work. He could therefore make statements neither about the particular models he use nor about the relation between different models (Bindernagel and Eilks 2009. Reproduced by permission of The Royal Society of Chemistry)

In accordance with the traditionally used, content-oriented structure of most German curricula, we can recognize three different levels: (I) a level of simple discrete particles, (II) a level of atoms and atomic structure, and (III) a level of covalent bonding and molecular structure. The lines in Fig. 1 represent the respective numbers of teachers choosing a particular path from one submicroscopic concept to another (Bindernagel and Eilks 2009).

All but one of the teachers approached the submicroscopic level by introducing a simple model of discrete particles. This is in line with most of the official syllabi in the different German states (the “Länder”). Half of the teachers select a historical approach when moving toward the particle level and refer to the ancient Greek philosophers. This decision is not based on the syllabi. Others take a more pragmatic approach stemming from phenomena without referring to the history of chemistry.

Nearly all of the teachers introduce a simple particle model at this point, in which particles are represented as hard spheres. Only 3 of the 28 teachers vary their pictorial representations of particles in their illustrations. This is quite disturbing, since an extremely controversial debate has raged in various German-language journals for the teaching of chemistry in recent years. In the discussion, it was derived from empirical evidence not choosing spheres as a standard tool but rather representing particles various physical shapes to avoid confusion among learners that these spheres on this stage represent the discrete particles, while later the same illustration is used for atoms within a first model of atoms (e.g., Eilks and Moellering 2001; in English see Eilks et al. 2007). The related debate, namely, that of making a clearer distinction between the level of discrete particles and that of atoms, seemed to have had no influence on the teachers interviewed (Eilks et al. 2002; in English Eilks et al. 2007; parallels in Hesse and Anderson 1992).

In their overall approach and advice to younger colleagues, most in-service teachers suggested teaching chemistry at the submicro level based on the history of science. This was explicitly stated by 22 out of 28 of the participants. They suggest variation in models to structure the chemistry curriculum, starting, for example, with a simple particle model, via the Dalton atomic model, toward models of atomic structure and of bonding theory. These last steps should be operationalized using different models ranging from the ideas of Rutherford, Thomson, and Bohr, followed up with models of bonding (e.g., ball and stick), the VSEPR model, or orbital theory. However, several teachers repeatedly mixed up different historical models when discussing their curricular approach varying different models. They either combined them into hybrid models (Justi and Gilbert 2002) or, at the least, did not differentiate clearly between differing models. This happened, for example, in the case of the simple particle model of discrete particles and the Dalton atomic model (see above):

> You mean another particle model? I wouldn’t know of any other. Yes, I always say particle, but that is the Dalton model, right? I don’t call it that, but that is the model actually. The atoms are small, compact spheres like billiard balls.

Most of the teachers were not aware of the difference between the discrete sphere particle model referring to kinetic gas theory, the ancient Greek particle model, or the Dalton model. Also they do not seem to be fully aware that Dalton’s historic model is not identical to the Dalton atomic model used in most German classrooms, textbooks, and curricula (Table 1). In these teachers' minds, their personal teaching approach seems to accurately represent the history of science:

> At the beginning of 8th grade, the sphere particle model, followed by the Dalton model in the middle or at the end of the year. 9th grade Rutherford, in the 10th grade or maybe the end of 9th grade, Bohr's model. In 10th grade we use the electron ball cloud model, which is of course a kind of orbital model and also lends itself as a model for chemical bonding … You can pretty much forget the Bohr model. Although substances' color can be satisfactorily described with it.....You always have to roll out a model whenever you want to explain something. This means following the historical development of models. That's the same order (that the models were developed in). This fits the pattern of teaching. I wouldn't want to deviate from it.

The history-driven approach seems to be somewhat self-evident. In their view, a variety of models must be used in the curriculum. Several teachers called it the "classical approach":

> It is such a classical approach just at this point, where one moves from Dalton's atomic model to Thomson's watermelon model and then on to Rutherford's model.

Those teachers following the historical approach use three to seven different models. But the more models the teachers use, the more often connections between the models seemed to be somewhat unstructured:

> It naturally starts somewhere with Dalton and then, Rutherford, Dalton, then eventually you end up at Bohr's atomic model … in order to explain certain basic concepts. There's always a big fight, I think, about whether Bohr's atomic model is very limited or not and that we should bring in the orbital model somewhere … I usually stay with the Bohr model, in any case for the basics I stop there … definitely, because you can use it well for the electron pair repulsion model, then yes. You can theoretically show the spatial structure of compounds or electron bonding … Now I have to mention Democritus, maybe it's tied to such a term. At the very beginning comes the particle idea – spherical particles, but that doesn't have to do with the atomic model…

The number and selection of models vary (Fig. 1). Nevertheless, there were some points of common agreement. This included use of the Rutherford gold foil experiment and eventually reaching the atomic model in the sense of an atom with a nucleus surrounded by discrete shells:

> I like to use the nucleus-shell model. I find that Rutherford and his idea are actually very important. I try to make this evident – I hit against objects and such, as if it is unfathomable that there isn't supposed to be anything there. [The teacher smacks his hand against the wall as he explains this] So developing this belief that something is solid and yet composed of almost nothing is really difficult to bring across and, in effect, you can only try to make it interesting and to prepare yourself so that you maybe succeed by using anecdotes. And the gold foil is naturally somehow the key.

A pedagogical justification for choosing the history-driven approach was only given by a minority of the teachers. The approach seemed to be classical and self-evident for most of the teachers. Those few teachers actually naming reasons referred to the objectives of teaching about the nature of science. They argued that students should learn about the tentative nature of scientific theories by learning that historical models can and have been replaced and refined over time:

Table 1 Curriculum/teaching models in lower secondary chemistry

Model	Main idea(s)	Role within the curriculum
Approach to the particle level and a simple model of discrete particles		
Alchemy model		The Alchemy model is not a particle model. The Alchemy model is only used as an entryway into the history of chemistry
Ancient Greek Atomic model	Matter is made of smallest particles. These smallest particles cannot be split up any further by any means	Matter consists of smallest particles. The idea of having particles is one of the oldest ideas in the history of chemistry
Simple model of discrete particles (without exclusively using spheres)	Matter consists of particles with only empty space between them. The particles are in constant motion and constantly crash into one other. Particle motion increases with rising temperature	Explanation of the states of matter, their changes, diffusion, and solubility. Spheres are not used to avoid mix-ups with the later-used description of atoms
Sphere particle model	Matter consists of particles modeled by solid spheres. Between the spheres is empty space. The spheres are in constant motion and constantly crash onto one other. Particle motion rises with increasing temperature	Explanation of the states of matter, their changes, diffusion, and solubility
The level of atoms and atomic structure		
Dalton atomic model	Atoms are spheres, solid, and indivisible. Atoms are connected to form chemical compounds	Explaining reactions of elemental substances. Conservation of mass. Law of constant proportions. Sometimes used for illustrating chemical formulae
Thomson atomic model	Atoms are spheres. Atoms contain positively charged protons and negatively charged electrons. Protons and electrons are spread around in the atom like the seeds in a watermelon	Introduction of subatomic particles: protons and electrons
Rutherford atomic model	Atoms are spheres. The atom contains a small nucleus. The nucleus contains the positive charge and nearly the entire atomic mass. The shell contains the electrons and is more or less empty space	Introduction of a nuclear shell structure of the atom
Bohr atomic model	Atoms are spheres. The nucleus is small and consists of protons and neutrons. The shell is made up of the electrons, which are in different shells following specific rules. The outer shell makeup is the cause of the main aspects of chemical behavior	Explanation of redox reactions, ionic bonding, and PSE and providing the base for models of covalent bonding. Sometimes another model with reference to Bohr is introduced also. This model parallels the shell of the atom with the solar system

(continued)

Table 1 (continued)

Model	Main idea(s)	Role within the curriculum
The level of covalent bonding and molecular structures		
Electron pair repulsion model	Within the outer shell of the atom, the electrons form pairs. A structure is formed so that each two of the pairs – in chemical bonds or lone pairs, but not in double or triple bonds – have the largest distance from one other	Explanation of molecular geometry, i.e., the water molecule and organic compounds or solid state structures. Curriculum model based on the VSEPR model by Gillespie and Nyholm
Ball cloud model	Electrons within the atom are placed in cloud spheres. Every cloud sphere can contain a maximum of two electrons. Rules for placing electrons into the clouds are defined by the Pauli principle and statistically based positions for cloud spheres. The cloud spheres within the atom attempt to form a symmetric structure around the nucleus	Explanation of molecular geometry, i.e., organic compounds. Approach combines the ideas of the Bohr atomic model with aspects of the orbital model. Curriculum model based on the ideas of the model by Sidgwick/Powell and Kimball/Bent
Orbital model	Electrons within the atom are placed within orbitals. Orbitals are specific geometric structures that allow for explaining the geometry of different types of covalent bonds	The form and orientation of the orbitals in most cases is used without introducing the theoretical background (discussing the wave nature of the electron, Schrödinger's equation, "probability of finding in some location," etc.). Curriculum model based on the orbital model

The models employed are inconsistent with the respective scientific or historical model in every case. The role within the curriculum gives only the main aspect(s) (Bindernagel and Eilks 2009)

> That's something that Dalton's model doesn't explain; instead you need a differentiated atomic model. OK, when the pupil reaches this point and says: We can't explain the phenomenon, with which we are currently faced, by using any model concepts that we already know. The modeling idea doesn't hold up and isn't differentiated enough. And then we continue just like scientists and look in the literature. What do we find there? What did other clever people from long ago find there? Then I introduce the Rutherford model.

Evidence of this approach's success was not discussed, and the teachers' view appeared to be more of a paradigmatic character. Combining this viewpoint with the teachers' ability to clearly distinguish between different models, including their professed understanding of the nature of scientific models and the history of science (Bindernagel and Eilks 2008; Sprotte and Eilks 2007), allowed us to make some careful conclusions as to whether this approach works in practice as well as it does in theory. This is clearly a question of whether teachers will be able to draw a comprehensible picture for their younger, less-motivated students in compulsory school chemistry lessons beginning with grades 5 and 6 (ages 11–12). This is highly dubious when we consider that these teachers (I) do not themselves have very well-developed concepts of the nature of models (Sprotte and Eilks 2007; Bindernagel and Eilks 2008), (II) are not able to distinguish and clearly explain the history of the different submicroscopic models, (III) have no clear pedagogical justification for switching between up to seven different models, and (IV) are unable to explain their strategies clearly to younger colleagues.

Three out of the 28 teachers did not use the history-driven approach. This group described a curricular approach oriented around meaningful contexts and the applications of chemistry. They stated that introducing explanations at the submicroscopic level should be performed, if such information is needed. They stated that there should be a search for internally coherent conceptual development. In their view, switching between different historic models reduces most students' motivation, because they do not understand the differences and contradictions between the models and do not have the necessary skills to develop metacognitive strategies for dealing with them. Three other teachers mentioned not being satisfied with the history-driven approach, but they had not found or could not ultimately decide upon an alternate teaching strategy.

Development of a Changed Teaching Strategy for the Submicro World

Participatory Action Research (PAR) to Innovate the Chemistry Curriculum

By the year 2000, a group of researchers and practitioners had initiated a Participatory Action Research (PAR) project in chemistry education (Eilks and Ralle 2002). The project focused on the curriculum on the submicroscopic world and was inspired by the increasing awareness of several group members of the incomprehensible breaks and barriers extant in the historical approach described above. Particularly relevant was the effect on younger pupils (ages 11–16) when they were confronted with a multitude of different models. These learners generally have neither an intrinsic motivation to understand exactly why modeling switches are necessary nor well-developed, metacognitive competence which is up to the task of reflecting upon the inherently tentative nature of the models selected (Eilks and Moellering 2001).

The project was named "New ways towards the particle concept" (Eilks and Moellering 2001; Eilks et al. 2007). The central objective of the project was the design and development of innovative and effective teaching strategies dealing with the particulate nature of matter and their related submicroscopic concepts in lower secondary chemistry teaching. This approach targets the development of lesson plans, the application of cooperative learning strategies, and the integration of new media into teaching and learning. The central idea was the development of an internally coherent conceptual structure of teaching submicroscopic concepts in chemistry, without any conflicts stemming from contradictions within the different parts of the curriculum. Hope was expressed that such an approach might allow students to better learn submicroscopic concepts in a focused fashion and leave learning about the tentative nature of models in another (later) position in the curriculum (Eilks and Moellering 2001).

The curriculum design process was accompanied by diverse approaches for evaluating its effectiveness. This evaluation focused primarily on learner achievement and understanding. It included learner acceptance of and the feasibility of the specifically selected teaching strategies, viewed from both the pupil and teacher perspective (e.g., Eilks 2005). Interviews with students (e.g., Eilks et al. 2007), analysis of learner artifacts, and written tests were also conducted (e.g., Eilks 2005). Classroom observations, teacher feedback in written format, and group discussion allowed the researchers to form a comprehensive picture of classroom activities. These sources of information were used for cyclically refining the teaching approaches but were also used to reflect on the teachers' ability and beliefs concerning the application of a changed teaching strategy as part of their continuous professional development (CPD) (Eilks and Markic 2011).

Issues of a Revised Teaching Strategy

The participating teachers stated that they faced problems when teaching the particulate nature of matter, and research confirms the persistence of many problems in this area. In Germany, various historical models are generally used as guidelines for teaching the particulate nature of matter (see above). From the teachers' viewpoint, these models are often insufficiently discussed by educators and by textbooks. These points came up in the initial meetings of the PAR group and stemmed from the teachers' self-reflection. Since then, much evidence has emerged that these are not merely the thoughts of individual teachers but rather a general problem in Germany's commonly applied curricula (see above Bindernagel and Eilks 2009). Analysis of German textbooks has also indicated that the most common teaching concepts are often inconsistently and unclearly differentiated from the perspective of using different models (Eilks et al. 2002, 2007). Unfortunately, some of the inconsistencies in chemistry textbooks resemble those reported in the literature concerning students' inattentiveness in model use (Eilks et al. 2002). Some textbooks seem to both perpetuate the common misconceptions spread among the students and create even more confusion (Eilks and Moellering 2001; Eilks 2003).

From this starting point, the PAR group decided to work out a new model approach for submicroscopic concepts which is internally consistent. The aim was to create a teaching strategy following a new model through the different stages of chemistry education. The group hoped to find a way to avoid gaps in student learning caused by the rapid switching from one model to another. The new model was seen not only as internally coherent but also as scientifically acceptable and compatible with students' learning capabilities, too. Similar ideas had been proposed by de Vos and Verdonk (1996). But their concept had only been worked out for the initial steps.

Our objective was to develop a coherent, well-tuned didactic sequence (including lesson plans and materials) for effectively teaching the particulate nature of matter in the entire lower secondary curriculum. Thus, the main guiding principle was coordinating the systematic development of students' knowledge over different stages of their education without introducing contradictions to previously introduced models. The objective was to avoid difficulties arising from the progressive adoption of new models which had played a role in the history of science. The progressive introduction of new and competing models (necessarily following their historical development) demands relevant "conceptual changes" in students' knowledge rather than a simple enrichment of their existing knowledge structures.

This can be explained using one example. Often, a first particle model is introduced using spheres to represent discrete particles (see above). The spheres in such models stand for all discrete particles as either molecules or ions (both mono- and multi-atomic), or they represent atoms in inert gases and metals. However, students at a later stage often face lasting difficulties in distinguishing such particles from their constituent entities. These entities are the single atoms that also are normally represented using spheres in the Dalton atomic model. Teachers often do not make a clear distinction between discrete particles and atoms. Thus, their students are quite often unable to do so, thereby facing many difficulties. This situation does not encourage pupils' motivation to be cognitively engaged in learning chemistry.

These difficulties have wide-reaching implications for students' later understanding of the chemical reaction. Chemical reactions are still introduced in several German textbooks as a "rearrangement of particles." Some of these textbooks do not make a clear distinction between the level of simple (discrete) particles and the level of atoms (Eilks et al. 2002, 2007). Therefore, students attempt to rearrange simple discrete particles to explain chemical reactions. Consequently, they may conceptualize chemical reactions as some kind of dissolution or diffusion (or just mixing). These, however, are physical processes and not chemical changes. The reason for this is that the sphere model of discrete particles does not facilitate the explanation of substance changes during chemical reactions (Fig. 2). The model does not allow for the composition of a pure substance as the product of a reaction between two initial substances, since such a product must be constructed of identical spheres representing the particles of the product. The formation of these spheres is not possible within the model. Additionally, the reaction from one initial substance into two or more products is not possible. (In Fig. 2 this would be the reverse reaction.) In this case, we should have one kind of identical spheres at the beginning and two or more kinds of particles after the completion of the reaction. This cannot be explained by any kind of "rearrangement" (Eilks et al. 2007). The participants in this action research group strongly believe that there is no need to introduce a "model of discrete particles to be represented by spheres" as suggested by most German textbooks. The group preferred the introduction of a "model consisting of discrete particles of different form and size" (Eilks and Moellering 2001).

The example described above is only a small part of the entire process and resulting structure. A second focal point of later discussions from within the group should also be discussed in brief. In the science education literature, there is also extensive

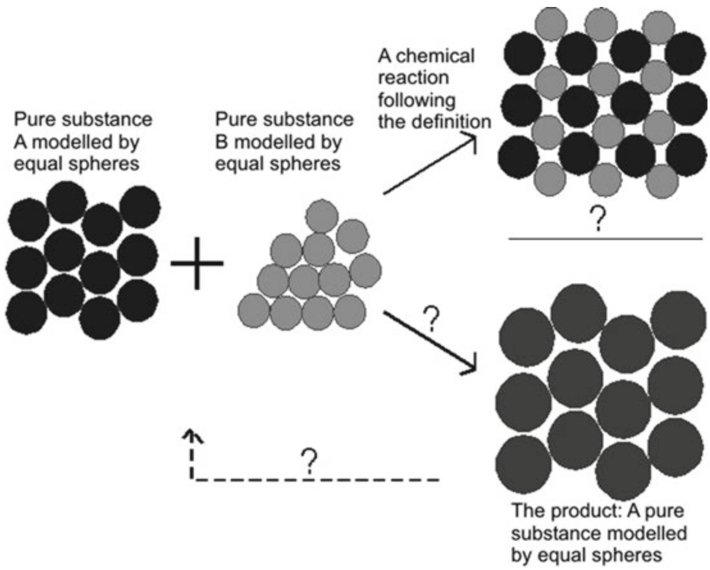


Fig. 2 Problems in explaining chemical reactions based on a simple model of spheres representing discrete particles

research about students' understanding of chemical bonding and how to introduce it (e.g., Levy Nahum et al. 2010). Some curricular approaches to chemical bonding intend to start from macro phenomena, like the lattice structure of salts, to derive the nature of bonding. Other suggestions start from atomic structure and approach bonding via the octet rule. In the later case, some curricula suggest a more static view based on a static understanding of electronegativity; others suggest a more dynamic approach by better elaborated electrostatic interpretations. There are also different opinions whether to introduce metallic, covalent, and ionic bonding as separate models of bonding to be applied in explaining different sorts of matter or whether to emphasize from the beginning a more holistic picture about what the three types of bonding have in common.

The teachers from this PAR group took up also this discussion but with much less emphasis than the discussion reported above. After having become familiar with the different suggestions of how to introduce bonding, the teachers did not feel similarly uncomfortable with their recent practice as they felt about the mixing of the particle and atomic models. Their teaching approach was the typical approach prevalent in most German curricula and textbooks. Following this approach, bonding is introduced starting from atomic structure by applying the octet rule for explaining ionic bonding. In later lesson plans, the nonpolar and polar covalent bonds are introduced, and in the end, metallic bonding is discussed. The approach is split into separate units to the different types of bonding. Thus, in this approach the different types of bonding are taught more or less independently.

In intense contention with the research literature, the teachers acknowledged that research suggests alternative teaching approaches which they never had heard and thought about. The teachers started developing an approach to a more holistic and dynamic approach integrating the three types of bonding into one lesson plan. But after initial experiences, the teachers considered that the benefits – if there were any under the specific circumstances the teachers work in – were not substantial enough to change their curriculum. Additionally, the teachers considered that this integrated approach may raise the degree of complexity, and felt that this may not be appropriate for students of this age (grades 8–9, age range 14–15). In the end, the teachers decided to keep their strategy of introducing three independent types of bonding but to try to better network and reflect them after all the three types are introduced. At this point the teachers developed a small module making clear how the different types of bonding do relate to one another and that all three types are based on dynamic electrostatic principles. The later point was supported by using a computer tool in the base of Spartan Software to visualize electron density distributions in molecules and lattice structures. This module is up to now applied in the participating grammar schools. Students from the grammar schools in Germany in their vast majority continue education to upper secondary level. In upper secondary chemistry, often a quantum mechanic interpretation of bonding is introduced. The teachers thought that this addition might be a good preparation for those students opting for advanced courses in chemistry at upper secondary level. Those teachers working at the middle and comprehensive schools where students in most cases do not continue to upper secondary education decided to leave this module out for most of their learning groups.

Finally the PAR group over the time of about 5 years developed an outline for a curricular framework, which – from the teachers point of view – (I) takes the objective of the approach into account, (II) fits into the governmental guidelines outlined in the syllabi, and (III) starts curriculum structuring from a thorough analysis of students' misconceptions and learning impediments. In the end, an outline of key sentences was suggested as guidance for internally coherent teaching approaches. The approach tries to be as simple as necessary and to use as few as possible information and complexity; but nevertheless it is sufficient to explain all submicro-related topics of the entire lower German chemistry curriculum. The first step closely parallels the approach suggested by de Vos and Verdonk (1996). However, the discussion with the teachers also considered that not all final suggestions for the key sentences were completely able to avoid any potential misconceptions. One point, for example, was the question whether to teach metallic, covalent, and ionic bonding as three non-overlapping categories. Research suggests that this might cause misconceptions. However, the teachers – based on their experience and in line with their syllabus – preferred to stay with teaching the three types of bonding separately to keep complexity in teaching lower. From their point of view, the gain in clarity was outbalancing the potential mismatch with the scientific understanding of the relationship of the different types of bonding. The key sentences as they were suggested by the work of the PAR group are outlined in Figs. 3, 4, 5, and 6 (Eilks 2002).

- All matter consists of small particles.
- All these small particles do have some mass. But one never can see the small particles with the eyes, not even with the best microscopes. Nevertheless, a scanning tunneling microscope can make pictures of the small particles.
- Nothing exists between the small particles.
- The small particles are in constant motion. With a rise in temperature, their average motion increases; with a fall in temperature, their average motion decreases. At constant temperature the average motion of the small particles stays constant.
- Collision of two small particles occurs in a fashion where both particles maintain their kinetic energy.
- Between the small particles, forces of attraction and repulsion exist, which are strongly dependent on the distance between the particles.
- We can explain many different phenomena with the help of these key sentences onthe structure of particulate matter. But we still cannot draw any conclusions about the actual appearance of the particles. For such conclusions, we would need more information about both the individual building units composing the small particles and their inner structure.

Fig. 3 Key sentences at the discrete particle level

- The smallest particles out of which all substances are made are built from one or more types of building units called atoms.
- Atoms are spherical and are composed of a nucleus and one or more electron shells. The diameter of the nucleus is only about 1/10,000 to 1/100,000 of the total atomic diameter. The nucleus contains almost the entire mass of the atom.
- Atoms are made up of protons, neutrons, and electrons. In an electrically neutral atom, the total number of protons equals the total number of electrons.
- The nucleus contains the protons and neutrons. Protons are positively charged; neutrons are neutral. Atomic nuclei are not changed by chemical reactions or electrical processes. Nuclei only change through radioactive decay,nuclear fission, or nuclear fusion.
- The electron shells contain electrons, which move both inside the atom and – under certain conditions – between atoms. Electrons are negatively charged.They are found in differing energy levels within the electron shell. We can imagine that these levels form several shells at varying distances from the nucleus. The innermost shell can hold 2 electrons, the next two 8, and the fourth18. It is impossible to say exactly where a given electron is inside the shell at any given moment. Atoms with the same electron configuration in their outermost shell as the noble gases (8 electrons or an"octet") are especially stable.
- Each of the more than 100 chemical elements has a characteristic number of protons in the nucleus. It is possible for the number of neutrons in the nucleus to vary among atoms of the same element. In thiscase we call them isotopes of this element.

Fig. 4 Key sentences at the atomic structure level

There are three different classes of chemical bonds:

a) *Ionic bonds:* Ionic bonds form between anions (negatively charged particles) and cations (positively charged particles), which attract one another electrostatically due to their opposite charges. This attraction works on all directons equally. The structure of ionic substances (these include mainly what we call salts) arises at the particle level through the packing together of the ions based on their size, shape, and charge.

b) *Metallic bonds:* Metallic bonds occur between metal atoms. These atoms in a metallic structure are unable to donate electrons to a specific partner or to accept electrons from same in order to achieve the noble gas configuration. For this reason, the electrons in the outermost shell disperse between all of the metal atoms. This is a favorable condition and leads to typical metallic behavior, like good electrical conductivity. The dispersal of electrons is the same in all directions. The structureof substances formed through metallic bonds, also called metals, arises at the particle level through the packing together of the ions based on their size.

c) *Covalent bonds (electron pair bonds):* Covalent bonds form between atoms which share two electrons in a bond which allows both to achieve the noble gas configuration. The covalent bond lies between both atoms and is said to be "shared". Depending on the type of atoms bound together and their individual ability to attract electrons toward themselves (electronegativity), the electrons in the bond can be skewed in varying degrees toward one of the bonding partners (a polarized bond). The structure of substances formed through covalent bonds arises at the particle level through further rules, which are summed up by the structural concepts describing the various types of covalent bonds.

Fig. 5 Key sentences at the level of different types of bonding

- Covalent chemical bonds are made of two electrons, which are located between the two bonded atoms in the form of a bonding electron pair.
- In atoms with more than one bond, the bonds separate themselves spatially, so that they maintain the greatest amount of separation from one another possible.
- In the case of double or triple bonds, the spatial structure of the bond is described as if only a single bond were present.
- If nonbonding electron pairs are present in addition to the covalent bond in the valence shell, they must also be considered. The structure of the resulting molecule must space the bonding and nonbonding pairs of electrons, so that they maintain the greatest amount of spatial separation from one another possible.
- In the simplest cases, the arrangement of the bonds around an atom yields:
  - A linear structure for a total of 2 bonds and/or nonbonding electron pairs
  - A trigonal planar structure for a total of 3 bonds and/or nonbonding electron pairs
  - A tetrahedral structure for a total of 4 bonds and/or nonbonding electron pairs
- The repulsion of the free electron pairs toward each other and covalent bonding pairs is somewhat larger than repulsion of the covalent bonds toward one another.This can lead to light discrepancies in the expected arrangements between the atoms. Such changes in bonding angles and positioning can also be caused when one of the bonding partners is extremely large or when the bonds are strongly polarized toward one of the partners.

Fig. 6 Key sentences for the level of molecular structure

Experiences

Since 2000, the approach described above has been applied to more than a hundred learning groups by the teachers in the PAR group and by teachers trained in in-service training courses. From the accompanying research studies (e.g., Eilks 2005; Eilks et al. 2007) and the feedback provided by the teachers, the approach has provided educators with a more finely tuned, and therefore a more motivating, approach for the entire German lower secondary school chemistry curriculum (ages 10–16). This is the time span, where chemistry education is compulsory for all German students.

The applicability of the approach presented here was shown by its implementation in different schools. In the last 10 years, this strategy was operationalized through an entire curriculum published in a series of new textbooks for lower secondary chemistry classes in Germany. By becoming textbook authors, members of the PAR group developed a new curriculum that, along with dealing with all other parts of the syllabi, is structured along the guideline worked out by the group (e.g., Eilks and Bolte 2008).

The teaching approach was also influential in implementing the new German science education standards in 2004 (KMK 2004). These national standards led to new syllabi for several of the German states in their core curricula, e.g., in the case of Lower Saxony (Ministry of Education in Lower Saxony 2007). New curricula now exclude building teaching efforts around a special, compulsory sequence of historical models in favor of structuring teaching plans toward the structure of matter. Nevertheless, most teaching practice in Germany is still unaffected by this change, as can be seen in the exploratory study reported on in the first half of this chapter (Bindernagel and Eilks 2009).

Conclusions

The study on the teaching pathways chosen by experienced German chemistry teachers reveals a predominant belief among teachers that teaching submicroscopic concepts needs to be taught as a sequence of different models. However, these concepts are often poorly elaborated by teachers, and the justification for them is rarely reflected upon. This study also shows that teacher content knowledge (i.e., about chemistry's historical development) and their pedagogical content knowledge sometimes is lacking in correctness and coherence (Bindernagel and Eilks 2008, 2009). Only a very few teachers seem to be aware of the large amounts of empirical evidence available about teaching submicroscopic concepts. Accordingly, they do not change their teaching approaches.

Yet the second study described here shows that it is possible to use educational evidence of students' alternate conceptions and learning difficulties to systematically construct an alternative curricular structure. The Participatory Action Research (PAR) project described documents that it is possible to teach submicroscopic concepts properly by using an internally coherent conceptual structure for the whole range of lower secondary science curricula. Applying this knowledge in textbook form incorporating schools, teachers' experiences, and PAR research results proves that its application can be feasibly and successfully carried out in a motivating fashion.

Nevertheless, only 6 out of 28 in-service teachers were either in favor of or even searching for alternative pathways for submicroscopic explanations. Only 3 of the 28 were already applying an altered approach. There seems to be a major problem in the areas of implementation and continuous professional development. Although in-service courses were given explaining the alternative approach and many articles have been published in German chemistry teaching journals, application of nontraditional teaching methods seems to be only rarely attempted.

Thus, our conclusion must be stated as follows. Change in the curriculum is possible. Alternative, research-based pathways on misconceptions, which take into account coherent conceptual development, are both feasible and promising. Nevertheless, change in classroom practices is much harder to accomplish than might be wished. Alternative approaches require time and must be both understood and accepted by teachers. This seems to be a much more difficult and longer road than the simple development of a new curricular structure.

References

Anderson, B. (1990). Pupils' conceptions of matter and its transformations (age 12–16). *Studies in Science Education, 18*, 53–85.

Bindernagel, J. A., & Eilks, I. (2008). Modelle und Modelldenken im Chemieunterricht und ein Einblick in das Verständnis von erfahrenen Chemielehrkräften [Models and thinking in models in chemistry teaching and insights into the knowledge of experienced chemistry teachers]. *Chemie konkret, 15*, 181–186.

Bindernagel, J. A., & Eilks, I. (2009). The roadmap approach to portray and develop chemistry teachers' pedagogical content knowledge concerning the particulate nature of matter. *Chemistry Education Research and Practice, 10*, 77–85.

De Vos, W., & Verdonk, A. H. (1996). The particulate nature of matter in science education and in science. *Journal of Research in Science Teaching, 33*, 657–664.

Eilks, I. (2002). Von der Rastertunnelmikroskopie zur Struktur des Wassermoleküls – Ein anderer Weg durch das Teilchenkonzept in der Sekundarstufe I (Teil 1 und 2) [From scanning tunneling microscopy towards the the structure of the water molecule – An alternative way through the particle concept in lower secondary teaching (Part 1 and 2)]. *Chemie und Schule (Salzbg.), 17*(3), 7–12 and *17*(4), 2–6.

Eilks, I. (2003). Students' understanding of the particulate nature of matter and misleading textbook illustrations. *Chemistry in Action, 2003*(69), 35–40.

Eilks, I. (2005). Experiences and reflection about teaching atomic structure in a jigsaw classroom in lower secondary level chemistry lessons. *Journal of Chemical Education, 82*, 313–320.

Eilks, I., & Bolte, B. (Eds.). (2008). *Chemie interaktiv (Ausgabe A)* [Chemistry Interactive; Issue A]. Berlin: Cornelsen.

Eilks, I., & Markic, S. (2011). Effects of a long-term participatory action research project on science teachers' professional development. *Eurasia Journal of Mathematics, Science and Technology Education, 7*, 149–160.

Eilks, I., & Moellering, J. (2001). Neue Wege zu einem faecherübergreifenden Verständnis des Teilchenkonzepts [New ways towards an inter-disciplinary understanding of the particle concept]. *Der Mathematische und Naturwissenschaftliche Unterricht, 54*, 421–427.

Eilks, I., & Ralle, B. (2002). Participatory action research within chemical education. In B. Ralle & I. Eilks (Eds.), *Research in chemical education – What does this mean?* (pp. 87–98). Aachen: Shaker.

Eilks, I., Leerhoff, G., & Moellering, J. (2002). Was ist eigentlich eine chemische Reaktion? [What in fact is a chemical reaction?]. *Der Mathematische und Naturwissenschaftliche Unterricht, 55*, 84–91.

Eilks, I., Ralle, B., Markic, S., Pilot, A., & Valanides, N. (2006). Ways towards research-based science teacher education. In I. Eilks & B. Ralle (Eds.), *Towards research-based science teacher education* (pp. 179–184). Aachen: Shaker.

Eilks, I., Möllering, J., & Valanides, N. (2007). Seventh-grade students' understanding of chemical reactions – Reflections from an action research interview study. *Eurasia Journal of Mathematics, Science and Technology Education, 4*, 271–286.

Eilks, I., Witteck, T., & Pietzner, V. (2009). Using multimedia learning aids from the Internet for teaching chemistry – Not as easy as it seems? In S. Rodrigues (Ed.), *Multiple literacy and science education: ICTS in formal and informal learning environments* (pp. 49–69). Hershey: IGI Global.

Feierabend, T., Jokmin, S., & Eilks, I. (2011). Chemistry teachers' views on teaching 'climate change' – An interview case study from research-oriented learning in teacher education. *Chemistry Education Research and Practice, 11*, 85–91.

Garnett, P. J., Garnett, P. J., & Hackling, M. W. (1995). Students' alternative conceptions in chemistry: A review of research and implications for teaching and learning. *Studies in Science Education, 25*, 65–95.

Grosslight, L., Unger, C., Jay, E., & Smith, C. L. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*, 799–822.

Hesse, J. J., III, & Anderson, C. W. (1992). Students' conceptions of chemical change. *Journal of Research in Science Teaching, 29*, 277–299.

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning, 7*, 75–83.

Justi, R., & Gilbert, J. K. (2002). Models and modeling in chemical education. In J. K. Gilbert, O. de Jong, R. Justi, D. F. Treagust, & J. H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 47–68). Dordrecht: Kluwer.

KMK. (2004). *Bildungsstandards im Fach Chemie für den mittleren Schulabschluss* [Educational standards for Chemistry concerning the finishing of lower secondary education]. Bonn: KMK.
Krnel, D., Watson, R., & Glazar, A. (1998). Survey of research related to the development of the concept of 'matter'. *International Journal of Science Education, 20*, 257–289.
Levy Nahum, T., Mamlok-Naaman, R., Hofstein, A., & Taber, K. S. (2010). Teaching and learning the concept of chemical bonding. *Studies in Science Education, 46*(2), 179–207.
Mayring, P. (2000). Qualitative content analysis. *Forum: Qualitative Social Research, 1*(2). Retrieved February 1, 2002, from www.qualitative-research.net/fqs
Meijer, M., Bulte, A. M. W., & Pilot, A. (2009). Structure property relations between macro and micro representations: Relevant meso-levels in authentic tasks. In J. K. Gilbert & D. F. Treagust (Eds.), *Models and modeling in science education* (Vol. 4, pp. 195–214). Dordrecht: Springer.
Ministry of Education in Lower Saxony. (2007). *Kerncurriculum für die Naturwissenschaften* [Core curriculum science]. Hannover: Ministry of Education.
Sprotte, J. A., & Eilks, I. (2007, 21–25 August). *Introducing the particulate nature of matter – Results from a case study on experienced German Science Teachers' PCK of models and modeling*. Paper presented at the 6th Conference of the European Science Education Research Association, Malmoe.
Wildt, J. (2006). Research-oriented learning in teacher education. In I. Eilks & B. Ralle (Eds.), *Towards research-based science teacher education* (pp. 5–12). Aachen: Shaker.

What Do We Know About Students' Beliefs? Changes in Students' Conceptions of the Particulate Nature of Matter from Pre-instruction to College

Faik Ö. Karataş, Suat Ünal, Gregory Durland, and George Bodner

Introduction and Organization of the Review

Studies that have probed students' views of a wide range of concepts have shown that students at every stage of education hold inappropriate, alternative beliefs about basic scientific concepts that differ significantly from the commonly accepted beliefs of subject-matter experts in the physical sciences (see, e.g., Fleer 1999; Nakhleh 1992; Orgill and Sutherland 2008; Osborne 1982; Palmer 1999, 2001). Some of these concepts are so basic; they can be considered "threshold concepts" upon which the understanding of the physical sciences not only can but must be built. Meyer and Land (2006) argued that "a threshold concept can be considered as akin to a portal, opening up a new and previously inaccessible way of thinking about something" (p. 3). Until or unless fundamental threshold concepts are grasped by students, related concepts cannot be fully understood.

The particulate nature of matter (PNM) may be one of the most crucial and fundamental examples of a threshold concept in chemistry (Ayas et al. 2010; Haidar and Abraham 1991; Novick and Nussbaum 1978, 1981; Özmen et al. 2002; Papageorgiou and Johnson 2005; Valanides 2000). The PNM not only plays a fundamental role in the learning of the sciences (Ben-Zvi et al. 1986; Haidar and Abraham 1991), the growing emphasis on nanoscience and nanotechnology (Ratner and Ratner 2003) increases the importance of an understanding of the fundamental aspects of the PNM, because explanations of the properties of substances and their

F.Ö. Karataş • S. Ünal
Department of Secondary Science and Mathematics Education,
Karadeniz Technical University (KTU), Sogutlu, 61355 Trabzon, Turkey
e-mail: faikozgurkaratas@hotmail.com; unal_suat@hotmail.com

G. Durland • G. Bodner (✉)
Department of Chemistry, Purdue University, West Lafayette, IN 47907, USA
e-mail: gmbodner@purdue.edu

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_11,

interactions on the nanoscale presume a basic understanding of the particulate theory of nature.

Because of its importance, the PNM is one of the most essential concepts in science education standards for primary and secondary education (NRC 1996; Singer et al. 2003). Probing students' beliefs about the PNM therefore becomes a crucial step in developing a better understanding of their views of basic science. Work of this nature can also provide the basis for new teaching techniques that help students overcome the limitations of their naïve knowledge and alternative frameworks (Schoon and Boone 1998).

Definitions

The phrase "the particulate nature of matter" (PNM) will be used in this chapter to describe phenomena ranging in size from individual atoms (≈0.1 nm) up to the nanoscale (≤100 nm). Both subatomic particles (electrons, neutrons, and protons) and the mesoscale (between 0.1 and 1 μm) will be excluded, as will objects that would be described as macroscopic (>1 μm).

No attempt will be made to differentiate between the ideas of "students' beliefs" and "conceptions." Both terms will be used to refer to the mental models (Bodner et al. 2005) students create, hold, and often defend. These terms will therefore be used to describe the complex pictures or schema in students' minds that can be viewed as their justified beliefs, views, or conceptions, regardless of whether they are similar to or different from the accepted ideas and explanations of subject-matter experts (Hewson and Hewson 1984; Nakhleh 1992; Treagust 1988).

Studies of the PNM

A comprehensive literature search was performed based on two criteria. First, articles were selected exclusively from peer-reviewed journals, with the exception of an early report prepared by Brook et al. (1984). Second, articles that describe curriculum developments designed to improve students' conceptions of the PNM were excluded.

Studies of the PNM were sorted into four categories according to participants' level of education: pre-instruction, elementary-middle school, high school, and college. A fifth category of cross-age studies was created that probed students' views of the PNM from a developmental perspective. Data extracted from the various studies included information about the participants, the data collection methods, and brief descriptions of the students' conceptions of the PNM. A summary of the studies was then created for each of the categories, organized in terms of increasing grade level.

Table 1 Summary of studies at pre-instruction level

Study	Participants	Data collection	Results
Nakhleh and Samarapungavan (1999)	15 elementary students from grades 1 to 4 (7–10 years old)	Interview	Most students had macro-continuous or macro-particulate, although some had micro-particulate frameworks
Maskill et al. (1997)	300 students from three European countries (11–12 years old)	Word association test	Lack of particulate conception, ideas that were affected by cultural background

Pre-instruction

The two studies conducted on students who had never received formal instruction about the PNM are summarized in Table 1. Most of the pre-instruction students in the USA invoked macro-continuous and macro-particulate frameworks in which the children visualized matter in accord with its observable physical properties (Nakhleh and Samarapungavan 1999). The authors of this study noted, however, that a few students held a particulate view of matter before formal instruction. A comparison of the results of the two studies in this category suggests that the PNM was not part of the everyday linguistic culture in Europe during the late 1990s the way it was in the USA at that time (Maskill et al. 1997).

Elementary and Middle School

The subjects of the studies summarized in Table 2 are 4th to 9th grade students from whom data were collected after they encountered the PNM in their science classes. These studies therefore provide insight into how formal instruction shaped students' views. Almost all of these studies addressed the development of students' views of the nature of matter from a macroscopic, continuous, non-particulate model to a particulate, atomic/molecular view of matter. These studies showed (1) progress from early years to the end of middle school, (2) the existence of transitional conceptions (Johnson 1998), and (3) conceptions of matter within the sample population that were varied with increasing amounts of formal education.

Most of the students at each grade level held inappropriate, alternative ideas of matter or a macroscopic model of the composition and structure of matter. Students' views about the nature of matter were context based and could demonstrate a drastic change from one substance to another as the context changed from water to iron, wood, acid, and so on (Eilam 2004; Nakhleh et al. 2005; Renström et al. 1990). One student, for example, used a conceptual model that invoked the ideas of particles

Table 2 Summary of the studies at the elementary and middle-school level

Study	Participants	Data collection	Results
Özmen and Kenan (2007)	411 students from 4th through 6th grade	Questionnaire	Students attribute physical/macro properties of matter to its particulate/atomic properties. Many naïve conceptions and misconceptions regarding conservation of matter, distance between particles, macroscopic view of matter, macro-particulate, size of the particles, speed of particles
Singer at al. (2003)	587 7th grade students, around 13 years old	Drawings, interview, and multiple-choice test	61 % progress from the pretest to the posttest for the target class. More particulate theory expressions in drawings after instruction
Eilam (2004)	25 middle-school students, who had finished 7th grade	Open-ended written test	Four different views: macro view of matter, static particulate view of matter (PVOM), possibly dynamic PVOM that lacks explicit support for particle motion, and explicitly supported dynamic PVOM. Almost half of the students fit in the "macro view of matter" category
Nakhleh et al. (2005)	98th grade middle-school students	Interview	Better molecular understanding compared to 4th graders. Diversity and fragmentation in explanations, not a particular framework to explain every situation
Novick and Nussbaum (1978)	Around 180 8th grade students	Interview	The least understood aspects of the particle model were those that conflicted most with the students' everyday experience and perception of matter; 1/5 of the participants held continuous model of matter; 1/3 of the participants could not grasp empty space between particles (dust, germs, gases, air, or no space between particles)
Johnson (1998)	33 participants tracked from 7th to 9th grade	Interview	Four hierarchically ordered models of matter: continuous form, particles but in a continuous substance, attribution of physical characteristics to macroscopic particles, and submicroscopic particles. Transition models were also found. Slight improvement in students' PNM models from 7th through 9th grade

Margel et al. (2001)	1,302 students were tracked from the 7th through 9th grade	Questionnaire	Three main conceptions regarding the structure of matter were found: Materials are continuous substances; substances consist of particles; and substances consist of various molecules. There was a transition from continuous model of matter to molecular model of matter with increasing grade levels. Even though a conceptual change model with emphasis on a constructivist philosophy was employed, only half of the students' conceptions moved to the highest level, whereas 1/5 of the participants did not show any notable improvement
Renstrőm et al. (1990)	20 students from 7th, 8th, and 9th grade	Interview	Six hierarchically ordered structures of substances were held by students: homogeneous substances (continuous), substance units, substance units with "small atoms," aggregate of particles, particle units, and system of particles. It was also noted that the same participants adopted different conceptions of matter for different substances, problems, and phases. Students' understandings of the PNM were lowest with substances in gas phase

when talking about wood but argued that iron was continuous (Renstrőm et al. 1990). Nakhleh et al. (2005) suggested that applying and exemplifying the ideas of particles to multiple substances could help students generalize their conception of the PNM. Renstrőm et al. (1990) claimed that fewer students demonstrated an understanding of the PNM in gas phase than in solid and liquid phases.

Many of the studies in Table 2 noted that students have problems understanding the concept of empty space that results from the distance between particles in a gas, and, to a lesser extent, in liquids. They also had problems understanding the concepts of fluidity, rigidity, malleability, particle kinetics, the formation of compounds, and so on (Eilam 2004; Nakhleh et al. 2005; Novick and Nussbaum 1978; Özmen and Kenan 2007). It has been argued that the aspects of the PNM that are least understood are those that are the most inconsistent with the students' real-world experience (Novick and Nussbaum 1978).

High School

Table 3 summarizes the results of seven studies of students between the 9th and 12th grade. The methods of data collection for these studies included open-ended questions, interviews, and drawings. These studies suggested that high-school students' views of the nature of matter were similar to those of middle-school students. Brook and coworkers (1984), for example, reported that only 10–20 % of the 10th grade students had acceptable views of the PNM.

Students in these studies tended to use ordinary language when describing the PNM rather than the scientific language to which they had been introduced in class unless they were explicitly cued to do so (Cokelez and Dumon 2005; Haidar and Abraham 1991). When students used terms such as atoms, molecules, ions, protons, neutrons, or electrons, they seemed unaware of what they represented and subsequently held many misconceptions about these terms.

Even though the frequency of scientifically acceptable views of the PNM increased gradually with increasing grade levels, students usually attributed physical or macroscopic properties of matter to particles, atoms, or molecules and not the interactions between these particles (Ben-Zvi et al. 1986; Brook et al. 1984; Cokelez and Dumon 2005; Griffiths and Preston 1992). Students believed, for example, that atoms can melt, bend, weigh more in the solid phase than in the gas phase, have the same color as the bulk samples of the substance, and so on. Other examples of PNM misconceptions were: atoms are alive, atoms of the same element in gaseous and solid states have different properties, heat causes molecules to expand, and atoms and molecules are the same (Ben-Zvi et al. 1986; Griffin and Preston 1992; Brook et al. 1984).

Ayas and Özmen (2002) noted that approximately one-third of students' drawings contained representations of continuous forms of matter. Planetary orbital models, Lewis dot structures, and solid spheres were the most commonly drawn models for an atom (Cokelez and Dumon, 2005). It has been suggested that the

Table 3 Summary of the studies at high-school level

Study	Participants	Data collection	Results
Brook et al. (1984)	300 15-year-old students	Interview and open-ended tests	80 % or more students either did not associate particles with matter or held alternative frameworks about the PNM. 1/5 of the students held macroscopic views without any reference to the PNM. Attributing physical properties of matter to particles (melting or expansion with heat, arrangement of particles). Confusion among intermolecular forces: solid particles collide with each other or no force exists among particles
Ayas and Özmen (2002)	250 high school students: 150 9th grade and 100 10th grade	Drawings and open-ended tests	Nearly 1/3 of the students held misconceptions; 1/3 of the students also illustrated continuous ideas in their drawings. Many students did not use PNM in their explanations even though it was specifically asked for
Ben-Zvi et al. (1986)	288 10th grade students whose average age was 15	Open-ended test	Attribution of physical properties to particle properties: nearly half of the students believed that macroscopic properties of the matter and properties of atoms are the same. About 2/3 of the students asserted that atoms in different states have different properties
Nakhleh (1994)	14 11th grade students	Interviews and drawings	Four conception categories of matter in acid and base solutions: continuous model, particulate model, molecular model, ionic model
Cokelez and Dumon (2005)	930 students: 239 10th grade students (ages 15–16), 422 11th grade students (ages 16–17), and 269 12th grade students (ages 17–18)	Drawings and open-ended tests	The majority of 10th grade and many 11th and 12th grade students represented atom as a simple sphere. Use of a solar system model of atom increased from 10th grade to 12th grade. The majority of 10th grade students and about a quarter of 11th and 12th grade students chose the space-filling model. Confusion of terms: students confused atom and molecule; protons, neutrons, and electrons; and electrons and ion-charged particles
Griffiths and P reston (1992)	30 12th grade students from ten high schools	Interview	Numerous misconceptions were found. Most of these misconceptions were related to attribution of physical or macroscopic properties of matter to its atoms or molecules, such as: atoms in gas phase are lighter than in the solid phase, heat causes molecules to expand, molecules are solid spheres, and similar molecules in the same phase have different shapes. Other misconceptions were: atoms are alive; atoms have the same weight; and matter exists between atoms
Haidar and Abraham (1991)	183 11th and 12th grade students	Open-ended tests	Unless cued, students most often explained phenomena (dissolution, diffusion, effusion, and states of matter) in macroscopic context. More than half of the students used neither particulate terms (particles, granule, grain, ball, etc.) nor atoms or molecules. Very few students used atom and molecules in a scientific context

definition of a particulate model must be clear to avoid confusion with dust, dirt, and smoke. Moreover, limitations of particulate models of matter should be illustrated with care to avoid fostering misconceptions in which students think that the model is a magnified replica of a particle or a system of particles (Brook et al. 1984; Treagust et al. 2002).

College

Table 4 summarizes the results of four studies with college students. One study was conducted with science majors (Williamson et al. 2004), another focused on preservice science teachers (Özmen et al. 2002). The remaining studies were conducted with preservice elementary teachers (Gabel et al. 1987; Valanides 2000). Open-ended questions, drawings, and interviews were used to probe students' conceptions of the PNM at the college level. Although preservice elementary teachers (PSET) traditionally do not have a strong science background, the participants in the two studies conducted with PSETs exhibited progress toward an understanding of the PNM with increasing levels of understanding of atomic and subatomic concepts. The language of atomic-scale particles (such as atom, molecule, ion, electron, proton, and so on) was not part of the everyday language of the college-age students in these studies, unless it was explicitly cued (Williamson et al. 2004).

The college-level students in these studies failed to make the connections between observable macroscopic properties of matter and its particulate nature. Even though many of these students were aware of the notion that matter is made of particles/atoms, they still held inappropriate, alternative beliefs of the nature of these particles (Özmen et al. 2002). The majority of the college students thought that atoms are the smallest part of matter that retain the same physical properties as bulk samples of matter. Many of these students thought that molecules and atoms can expand, melt, and combine to form new molecules in much the same way that two drops of rain might combine with each other (Valanides 2000). These students also had problems with their understanding of the empty space between particles in a gas or liquid and the conservation of particles during chemical and physical changes. When specifically asked to explain everyday events using the particulate model of matter, many students were not able to do so (Özmen et al. 2002).

Implications for teacher education were discussed in studies that have been done with preservice teachers. Valanides' (2000) study, for example, provided strong evidence that the conceptual understanding of the PNM held by preservice elementary teachers' ideas can be similar to that of the children they will teach. As discussed elsewhere (Yip 1998), misconceptions held by preservice elementary teachers have the potential to trigger misconceptions for many generations of students who will be taught by these teachers. Valanides (2000) therefore suggested that teaching materials and instructional interventions that are based on the notion of conceptual change should be designed, implemented, and presented to both preservice and in-service teachers in order to avoid the transferring of misconceptions to their K-12

Table 4 Summary of the studies in college level

Study	Participants	Data collection	Results
Gabel et al. (1987)	90 preservice elementary teachers	Drawings and open-ended test	Inadequate understanding of the particulate nature of matter resulted in the lack of understanding of other concepts including conservation of particles and orderliness of particles
Özmen et al. (2002)	160 senior preservice science teachers	Open-ended test	55–70 % of the participants demonstrated sound and partial understanding. However, 1/4 held misconceptions. Participants' misconceptions of PNM affected their understanding of concepts of diffusion and osmosis. Many participants could not apply their theoretical knowledge of the PNM to explanations of everyday situations or events
Valanides (2000)	20 female preservice elementary teachers	Interview	Perceptual rather than conceptual understanding: attributing physical properties and changes to explain phenomena at molecular and atomic level. Participants had difficulty making connections between the observable macroscopic changes (i.e., the change in volume when mixing alcohol and water) with invisible molecular events. Lack of understanding of the molecular structure of matter, of empty space within matter, and of motion at the atomic level
Williamson et al. (2004)	1,066 college science majors	Open-ended and two-tier test	Unless cued, students tended to use everyday language to explain chemical phenomenon instead of using scientific terms such as atom(s), molecule(s), or ion(s). About 2/5 of the participant responses regardless of question type did not include any particulate terms

classrooms. Özmen and coworkers (2002) also suggested that students should be given more real-life examples that help them transform their theoretical knowledge to practical situations.

Cross-Age Studies

Table 5 summarizes the results of seven studies that collected data from across a wide range of participants' ages. These studies investigated students' views of the PNM from elementary school to the university level (Novick and Nussbaum 1981), among students from middle school through high school (Boz 2006), from middle school to the university level (Hwang 1995), from secondary to the tertiary level (Ayas et al. 2010), and from age 7 to 17 (Lofgren and Hellden 2008). Liu and Lesniak (2005) utilized data from the Third International Mathematics and Science Study (TIMSS) to investigate the development of the concept of matter in US children from elementary to high-school level. They then conducted a study that qualitatively probed how students develop conceptions of matter from elementary school to high school (Liu and Lesniak 2006).

The cross-age studies reported a moderate and sometimes slow improvement in students' conception of matter with increasing age and levels of education. They all noted, however, that many students at the high-school and college level held numerous misconceptions about the nature of matter and/or tended to rely on their perceptions of the world around them when it came to the structure of matter.

In a cross-age study of students from the secondary and tertiary level of education, Ayas et al. (2010) noted that the number of student responses that would be categorized as a "sound understanding" increased with educational level, except for a sample collected from first-year undergraduate chemistry students. Lofgren and Hellden (2008) found that about one-third of their participants either could not or did not have an image of the PNM. Similarly Novick and Nussbaum (1981) indicated that many college students conveyed representations of a continuous model of matter similar to results of studies of younger students, using responses that were descriptive rather than explanatory (Nakhleh et al. 2005; Brook et al. 1984). Boz (2006) reported results similar to those of Özmen et al. (2002) that suggested that students did not apply a particulate model to explain chemical phenomena unless it was specifically prompted. Studies in this category noted that students thought that particles were static, even in the gas phase, and did not believe there is empty space between particles (Boz 2006; Hwang 1995; Novick and Nussbaum 1981).

Liu and Lesniak (2005, 2006) argued that students' conceptions of matter are not developed in stair-like stages but rather in overlapping waves in which conflicting views of the nature of matter can coexist. Informal ideas about common substances such as water and air comprise the first wave, which usually occurs by the 3rd or 4th grade. The second wave occurs by the 7th grade as students develop an

Table 5 Summary of the studies in cross-age level

Study	Participants	Data collection CoCollectionMethod	Results
Lofgren and Hellden (2008)	23 students were tracked from the age of 7 to 17	Interview	Almost 1/3 of the students did not hold a particle idea at the age of 16; 1/5 of the students held scientific facts and knowledge but were not able to connect this knowledge with everyday situations; half of the students either used the particle model in scientifically (2/5) accepted ways or employed simple molecule models to explain the situation (3/5). Findings: (a) no distinction between molecule and substance (1/3); (b) scientific facts used in a nonproductive way in relation to the described situation (1/3); (c) the concept of a molecule used in a productive way as a small part of the substance(1/5); (d) a molecular model building on the scientific idea of the particulate nature of matter (1/5)
Liu and Lesniak (2006)	54 students from 1st grade to 10th grade	Interview	Student conceptions of composition of matter in general progress from macroscopic (i.e., ingredients, uses, and benefits up to 5th grade for water and up to 8th grade for vinegar and baking soda) to particulate (i.e., molecules and atoms; 4th grade and up). However, even 10th graders were found to have a difficult time to differentiating atoms, molecules, and particles from each other. It was also reported that students' conceptions of matter showed a different pattern of progress. Students began to realize water is made of particles after 5th grade, but this pattern was seen until 8th grade or higher for vinegar or baking soda. The researchers also claimed that even though there was progress toward conception of the particulate nature of matter by grade, overlap existed among students' conceptions of matter in different levels
Liu and Lesniak (2005)	TIMSS USA sample (a total of 32,922 students) from 3rd grade to 12th grade	Open-ended tests	Matter concept development in children from elementary ages to high school undergoes five overlapping waves rather than a stair mode. Teaching the PNM to 3rd and 4th grade students may not be very fruitful

(continued)

Table 5 (continued)

Study	Participants	Data collection CoCollectionMethod	Results
Novick and Nussbaum (1981)	576 students, including 83 5th and 6th graders; 339 7th, 8th, and 9th graders; 88 10th, 11th, and 12th graders; and 66 sophomore nonscience major students from a university	Open-ended and multiple- choice tests	Slight improvement in understanding of the PNM across grades. More students held a continuous model of matter for liquids than for a gas. Lack of understanding of the homogeneous distribution of gas and liquid atoms or molecules and the motion of particles. Empty space among particles was understood by only a few elementary and middle-school students; 37 % of high-school- and college-age students can picture this concept
Boz (2006)	6th grade ($n=40$), 8th grade ($n=60$), and 11th grade ($n=200$) students	Interviews and open-ended tests	Students' conceptions of the particulate nature of matter become more comprehensive with age. However, many students even in 11th grade still lack a basic understanding of the PNM. They also lack an understanding of particle motion in solids. If they were not cued about the PNM, students tended to explain phenomena via macroscopic properties. It was also found that scientists and students did not have a shared meaning of the term "particle." Most students thought that the fundamental particles of a matter should convey the same physical properties as matter on the macroscopic scale. Students' responses regarding PNM were inconsistent in different contexts
Hwang (1995)	1,029 students from junior high (8th and 9th grade), senior high (9th through 12th grade), and 1st and 2nd year university students	Multiple-choice test	Students could not apply PNM to explain the behavior of gases. Lack of understanding of PNM results in not understanding the gaseous phase. Particle motion and empty space between the particles (especially in gas phase) are two problematic issues
Ayas et al. (2010)	9th grade ($n=35$), 10th grade ($n=33$), 11th grade ($n=34$), freshman ($n=32$), and sophomore chemistry majors ($n=32$)	Drawings and open-ended tests	Many students, including college-age students, held misconceptions and had trouble explaining daily phenomena by applying particle theory. Students at different levels had a somewhat similar understanding of the PNM

understanding of the conservation of matter. The third wave is characterized by an understanding of chemical and physical properties of matter and the changes that might occur in these properties and occurs between the 8th grade (for well-prepared students) and 12th grade (for students without extensive training in chemistry.) The fourth wave, which involves the development of an understanding of a structural/compositional aspect of the concept of matter, occurs by the end of high school for students who take chemistry courses. The fifth wave, which involves the use of theories of bonding to explain and/or predict changes in matter, occurs at the university level (Liu and Lesniak 2005).

Liu and Lesniak (2006) also noted that the development of students' conceptions of different substances can occur at different ages. They argued that students begin to realize that water is made of particles after 5th grade, but it is not until 8th grade (or later) that they realize that the same is true for substances such as vinegar or baking soda. Boz (2006) also noted that students' views of PNM are inconsistent and context dependent.

Discussion

Certain patterns can be found in the studies of students' views of the particulate nature of matter.

- There is a pattern of epistemic development from macroscopic, continuous, non-particulate models toward particulate, atomic/molecular models with age and educational level.
- The overall pattern of epistemic development does not seem to depend on the country whose students are being studied.
- Because the epistemic development occurs in waves, rather than stages, students can simultaneously hold different PNM models for different substances (e.g., water versus vinegar) and for different phases (e.g., gases versus liquids or solids).
- The development process is relatively slow and occurs at different rates for different students. Even at the college level, participants can express naïve views of the PNM similar to those of elementary and middle-school students.
- Interventions are not effective in changing the natural development of the nature of matter in students' minds, and some aspects of PNM are not appropriate for certain age levels.
- Even when students grasp the scientific vocabulary of atoms, molecules, ions, electrons, etc., the enhanced vocabulary does little to alter their views of the nature of matter.
- Results obtained with college students demonstrate similar patterns to those observed with high-school students, and preservice elementary teachers often exhibit PNM views consistent with those held by the students they will teach.

Conclusions and Implications for Teaching and Future Research

In general, students fall along a spectrum of conceptual development from a macroscopic, continuous, non-particulate view of matter to an increasingly atomic/molecular model of matter between the pre-instruction and college level. Figure 1 tries to capture the idea that this development does not occur in a steplike, staged manner. It is characterized by transitional phases in which contradictory models of PNM can simultaneously exist for different substances.

Some aspects of students' early beliefs in the continuous nature of matter interfere with their understanding of related topics, including chemical reactions, gases, acid-base chemistry, solution chemistry, and a host of other topics (Johnson 1998; Nakhleh 1994; Novick and Nussbaum 1978). Even though many students may hold onto their early beliefs, their nature of matter framework becomes more diverse and fragmented with age and educational level. Some of this fragmentation may be the result of formal instruction or confusion about what is being taught. Course materials should therefore be rigorously examined for statements that can lead to student misunderstandings.

Because students' views of the PNM are contextual and often limited to a few substances, teachers should recognize the importance of using a variety of examples to promote students' ability to generalize the PNM to other substances. When teaching the concepts of atoms and molecules, for example, teachers should not only use the examples of water, iron plates, or copper wire. They should also utilize other

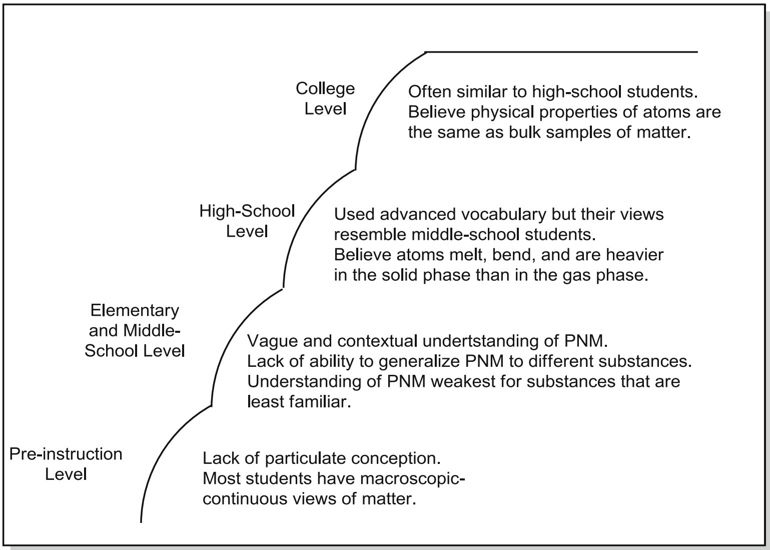


Fig. 1 Students' views of the particulate nature of matter (PNM) by grade level

examples, such as sugar cubes, sand, air (particularly N_2 and O_2), and so on (Boz 2006; Nakhleh et al. 2005; Renstrőm et al. 1990). It is also important to recognize that students' understanding of many aspects of the PNM is often naïve because what they are asked to learn conflicts with their everyday experiences (Novick and Nussbaum 1978). Teachers should also promote the idea that the chemical and physical properties of individual atoms or molecules are fundamentally different from the properties of bulk samples of matter.

Bodner et al. (2005) noted that students are explicitly introduced to the idea of *models* during their science courses, but they are rarely asked to take an active role in *modeling* – the process of constructing and evaluating scientific models. It has been suggested that the models used in teaching the PNM might support mental models that differ significantly from scientifically accepted models (Brook et al. 1984; Cokelez and Dumon 2005). Teachers should therefore explicitly involve students in the model development process. Care should also be taken to use language and terminology that is clear and avoids confusion (Brook et al. 1984; Cokelez and Dumon 2005; Treagust et al. 2002).

Liu and Lesniak (2005, 2006) raised an interesting issue when they questioned when and what aspects of the PNM should be introduced to students. Their results suggest that early elementary schooling may not be an appropriate time for teaching the compositional and structure aspects of matter.

It is widely accepted that teachers are one of the sources of students' science conceptions, either scientific or alternative. Therefore, any attempt to improve K-12 science education cannot be fully successful unless teachers are also included. Teacher preparation (as well as in-service professional development) should be reevaluated to inform teachers about misconceptions and ways in which they can be remediated so that they can design learning environments in which students' misconceptions are taken into consideration, and effective teaching methods and conceptual change strategies are employed (Özmen et al. 2002).

References

Ayas, A., & Özmen, H. (2002). A study of students' level of understanding of the particulate nature of matter at secondary school level. *Bogazici University Journal of Education, 19*, 45–60.

Ayas, A., Özmen, H., & Çalik, M. (2010). Students' conceptions of particulate nature of matter at secondary and tertiary level. *International Journal of Science and Mathematics Education, 8*, 165–184.

Ben-Zvi, R., Eylon, B. S., & Silberstein, J. (1986). Is atom of copper malleable? *Journal of Chemical Education, 63*, 64–66.

Bodner, G. M., Gardner, D. E., & Briggs, M. W. (2005). Models and modeling. In N. Pienta, M. Cooper, & T. Greenbowe (Eds.), *Chemists' guide to effective teaching*. Upper Saddle River: Prentice Hall.

Boz, Y. (2006). Turkish pupils' conceptions of the particulate nature of matter. *Journal of Science Education and Technology, 15*(2), 203–213.

Brook, A., Briggs, H., & Driver, R. (1984). *Aspects of secondary students' understanding of the particulate nature of matter*. Leeds: University of Leeds, Centre for Studies in Science and Mathematics Education.

Cokelez, A., & Dumon, A. (2005). Atom and molecule: Upper secondary school French students' representations in long-term memory. *Chemistry Education Research and Practice, 6*, 119–135.
Eilam, B. (2004). Drops of water and of soap solution: Students' constraining mental models of the nature of matter. *Journal of Research in Science Teaching, 41*, 970–993.
Fleer, M. (1999). Children's alternative views: Alternative to what? *International Journal of Science Education, 21*, 119–135.
Gabel, D. L., Samuel, K. V., & Hunn, D. (1987). Understanding the particulate nature of matter. *Journal of Chemical Education, 64*, 695–697.
Griffiths, A. K., & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*, 611–628.
Haidar, A. H., & Abraham, M. R. (1991). A Comparison of applied and theoretical knowledge of concepts based on the particulate nature of matter. *Journal of Research in Science Teaching, 28*, 919–938.
Hewson, P. W., & Hewson, M. G. (1984). The role of conceptual conflict in conceptual change and the design of science instruction. *Instructional Science, 13*, 1–13.
Hwang, B. (1995). *Students' conceptual representations of gas volume in relation to particulate model of matter*. Paper presented at the conference of the National Association for Research in Science Teaching, San Francisco.
Johnson, P. (1998). Progression in children's understanding of a 'basic' particle theory: A longitudinal study. *International Journal of Science Education, 20*, 393–412.
Liu, X., & Lesniak, K. (2005). Students' progression of understanding the matter concept from elementary to high school. *Science Education, 89*, 433–450.
Liu, X., & Lesniak, K. (2006). Progress in children's understanding the matter concept from elementary to high school. *Journal of Research in Science Teaching, 43*, 320–347.
Lofgren, L., & Hellden, G. (2008). A longitudinal study showing how students use a molecule concept when explaining everyday situations. *International Journal of Science Education, 31*(12), 1631–1655.
Margel, H., Eylon, B., & Scherz, Z. (2001). A longitudinal study of junior high school students' conceptions of the structure of materials. *Journal of Research in Science Teaching, 45*, 132–152.
Maskill, R., Cachapuz, A. F. C., & Koulaidis, V. (1997). Young pupils' ideas about microscopic nature of matter in three different European countries. *International Journal of Science Education, 19*, 631–645.
Meyer, J. H. F., & Land, R. (2006). *Overcoming barriers to student understanding: Threshold concepts and troublesome knowledge*. Oxon: Routledge.
Nakhleh, M. B. (1992). Why some students don't learn chemistry. *Journal of Chemical Education, 69*, 191–196.
Nakhleh, M. B. (1994). Students' models of matter in the context of acid-base chemistry. *Journal of Chemical Education, 71*, 495–499.
Nakhleh, M. B., & Samarapungavan, A. (1999). Elementary school children's beliefs about matter. *Journal of Research in Science Teaching, 36*, 777–805.
Nakhleh, M. B., Samarapungavan, A., & Saglam, Y. (2005). Middle school students' beliefs about matter. *Journal of Research in Science Teaching, 42*, 581–612.
National Research Council (NRC). (1996). *National science education standards*. Washington, DC: National Academic Press.
Novick, S., & Nussbaum, J. (1978). Junior high school pupils' understanding of particulate nature of matter: An interview study. *Science Education, 62*, 273–281.
Novick, S., & Nussbaum, J. (1981). Pupils' understanding of particulate nature matter: A cross-age study. *Science Education, 65*, 187–196.
Orgill, M. K., & Sutherland, A. (2008). Undergraduate chemistry students' perceptions of and misconceptions about buffers and buffer problems. *Chemistry Education Research and Practice, 9*, 131–143.

Osborne, R. (1982). Science education: Where do we start? *Australian Science Teachers Journal, 28*, 21–30.
Özmen, H., Ayas, A., & Coştu, B. (2002). Determination of the science student teachers' understanding level and misunderstandings about the particulate nature of the matter. *Educational Sciences: Theory & Practice, 2*, 506–529.
Özmen, H., & Kenan, O. (2007). Determination of the Turkish primary students' views about the particulate nature of matter. *Asia-Pacific Forum on Science Learning and Teaching, 8*(1), 1–15.
Palmer, D. (1999). Exploring the link between students' scientific and nonscientific conceptions. *Science Education, 83*, 639–653.
Palmer, D. (2001). Students' alternative conceptions and scientifically acceptable conceptions about gravity. *International Journal of Science Education, 23*, 691–706.
Papageorgiou, G., & Johnson, P. (2005). Do particle ideas help or hinder pupils' understanding of phenomena? *International Journal of Science Education, 27*, 1299–1317.
Ratner, M., & Ratner, D. (2003). *Nanotechnology: A gentle introduction to the next big idea*. Upper Saddle River: Prentice Hall PTR.
Renstrőm, L., Andersson, B., & Marton, F. (1990). Students' conceptions of matter. *Journal of Educational Psychology, 82*, 555–569.
Schoon, J. K., & Boone, J. W. (1998). Self–efficacy and alternative conceptions of science of preservice elementary teachers. *Science Education, 82*, 553–568.
Singer, J. E., Tal, R., & Wu, H. K. (2003). Students' understanding of the particulate nature of matter. *School Science and Mathematics, 103*, 28–44.
Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education, 10*, 159–169.
Treagust, D. F., Chittleborough, G., & Mamiala, T. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education, 24*, 357–368.
Valanides, N. (2000). Primary student teachers' understanding of the particulate nature of matter and its transformations during dissolving. *Chemistry Education Research and Practice in Europe, 1*, 249–262.
Williamson, V., Huffman, J., & Peck, L. (2004). Testing students' use of the particulate theory. *Journal of Chemical Education, 81*, 891–896.
Yip, D.-Y. (1998). Identification of misconceptions in novice biology teachers and remedial strategies for improving biology learning. *International Journal of Science Education, 20*, 461–477.

Diagnostic Assessment of Student Understanding of the Particulate Nature of Matter: Decades of Research

Ajda Kahveci

Introduction

Student understanding in one of the most fundamental topics of chemistry, the particulate nature of matter, has been a research area of interest for quite a while. Student conceptions in this topic have been widely researched by numerous scholars for over three decades (i.e., Boz 2006; Griffiths and Preston 1992; Kokkotas et al. 1998; Liang et al. 2011; Nakhleh et al. 2005; Novick and Nussbaum 1978, 1981; Othman et al. 2008). Utilizing a wide range of assessment methods, the researchers most often referred to student conceptions that tended to differ from the views of the scientific communities as misconceptions or alternative conceptions. An important aspect was that assessment was approached as more of a learning than a grading tool. A range of implications from these studies suggested teaching methods for more informed understandings of the particulate nature of matter.

The main purpose of this chapter is to provide an overview of diagnostic assessment research carried out to explore particulate nature of matter conceptions. In educational research, the particulate nature of matter ideas are closely related with physical or chemical phenomena such as phase transitions and chemical reactions as well as with the structure and composition of matter. Derived from science education research, de Vos and Verdonk (1996) made a list of ideas about particles in matter that are considered acceptable in science education. The eight points in the list include the following ideas: individual particles are too small to be seen and can be represented with small dots or circles; motion is a permanent feature of all particles relating to their average kinetic energy; there is a large empty space among gas particles as compared with the size of the particles themselves; there is a mutual

A. Kahveci (✉)
Chemistry Education Program, Department of Secondary Science and Mathematics Education, Faculty of Education, Çanakkale Onsekiz Mart University, Çanakkale, Turkey
e-mail: ajdakahveci@comu.edu.tr

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_12,

attraction between two particles, but the attraction between gas particles is negligible because of large separations between the particles; particles in solids are arranged in regular patterns close together, being able to only vibrate, while particles in liquids and gases are irregularly arranged and relatively free to move; different substances consist of different particles but particles of a certain substance are identical; a chemical reaction means rearrangement of atoms; an atom consists of a positively charged nucleus and negatively charged electrons, and the electrons play role in chemical bond formation and electric current.

The studies reviewed in this chapter assess student understanding about the particulate nature of matter corresponding to de Vos and Verdonk's (1996) list of ideas. Most of the studies focus on analyzing students' understanding of the majority of these notions via different items, questions, or probes (i.e., ideas about arrangement of particles in given substances as well as submicroscopic explanations of physical phenomena such as changes of state). A limited number of studies (i.e., Adbo and Taber 2009) target ideas related with atomic structure, subatomic particles, and their relation to chemical bonding and electric current.

As the first step of the review, a generalized search was performed over all databases on ISI Web of Knowledge by entering "partic* AND nature AND matter" as keywords in the Topic field. This search yielded 3,494 results, which then were refined by *Subject Areas* = (*CHEMISTRY*) narrowing down to 424 results. The resulting list was further refined by *General Categories* = (*SOCIAL SCIENCES*) and *Subject Areas* = (*EDUCATION and EDUCATIONAL RESEARCH*), leaving six most related references in the list. Lining up with the purpose of overviewing diagnostic assessment research, these articles were scrutinized for their being theory or research oriented writings. Particular attention was paid to an available assessment method and instrument specifically designed to elicit particulate ideas. Studies exploring understandings of other chemistry concepts (that may partly include particle ideas) were excluded from the pool [i.e., the study conducted by Pınarbaşı and Canpolat (2003) on solution chemistry concepts]. Finally, three of these references meeting the specific search criteria were included in the review.

The second step of the search targeted more narrowly any diagnostic assessment methods and instruments concerned with the particulate nature of matter ideas. For this purpose the keywords "particulate nature of matter" and "chemistry education" were used with the keywords "two-tier tests" and "diagnostic assessment" in different combinations over Web of Knowledge databases. For instance, when the keyword "particulate nature of matter" was entered along with "chemistry education" and "diagnostic assessment," choosing Topic as the search field, only one reference appeared. In order to access a larger pool, the keyword "particulate nature of matter" was left out and the search was repeated. This search yielded 80 results, which were refined by *General Categories* = (*SOCIAL SCIENCES*) and *Subject Areas* = (*EDUCATION and EDUCATIONAL RESEARCH*). The final list contained 14 references, 8 of which were publications in the medical field. One that was indirectly related to the topic was eliminated; finally, five references from this search were retrieved for the review.

A pool of publications based on these searches including the author's own work was generated. In some cases it was deemed important to access cited work; one problem with publications dated 1980s, 1990s, and earlier is the lack of keywords or incomplete keywords reducing their visibility in database searches. This situation required much effort to include important work. One way was to track the leading articles through the accessed publications. On the other hand, a large number of citing publications were not selected for inclusion in the review because their relation with the topic diagnostic assessment of particulate concepts was marginal at most. As the review is limited with the selected sample of published work, the conclusions drawn may or may not hold for a larger literature base. However, efforts were made to ensure that the majority of leading, most cited publications in the area of diagnostic assessment of particulate nature of matter conceptions are not left out.

For the analysis in this chapter, the selected work was classified based on research methodologies with a particular focus on the type and content of the diagnostic instruments used for data collection. Exemplars from the instruments for interested scholars and practitioners are provided within the text or in the Appendices upon permission obtained from the authors. The corresponding authors were contacted via electronic mail asking for their consent to include sections of their instruments in this chapter. When an instrument was not available, the authors were kindly asked if they would be willing to send it for inclusion.

The following section starts with an overview of the literature on diagnostic research on student understanding of the particulate nature of matter as classified based on research methodology. In the first part, intervention studies are described. The section on descriptive studies is followed with a review of studies concerned with two-tier diagnostic assessment in the various subject areas of chemistry, including the particulate nature of matter. The chapter concludes with a discussion and conclusions section based on main issues emerging from the review.

Diagnostic Assessment of the Particulate Nature of Matter

Educational research on diagnostic assessment of the particulate nature of matter ideas appears to be disproportionately distributed between two main designs of research. As illustrated in Fig. 1, the majority of the work in the area falls under the general category of descriptive studies, which are studies that describe a situation as completely as possible, in this case student understanding and misconceptions.

A limited number of studies, on the other hand, are intervention studies, also known as experimental research, in which a particular treatment or method is expected to influence some outcomes (Fraenkel and Wallen 2003). Both groups are described in the following sections, with a particular emphasis on the research methodology and the instruments that were utilized.

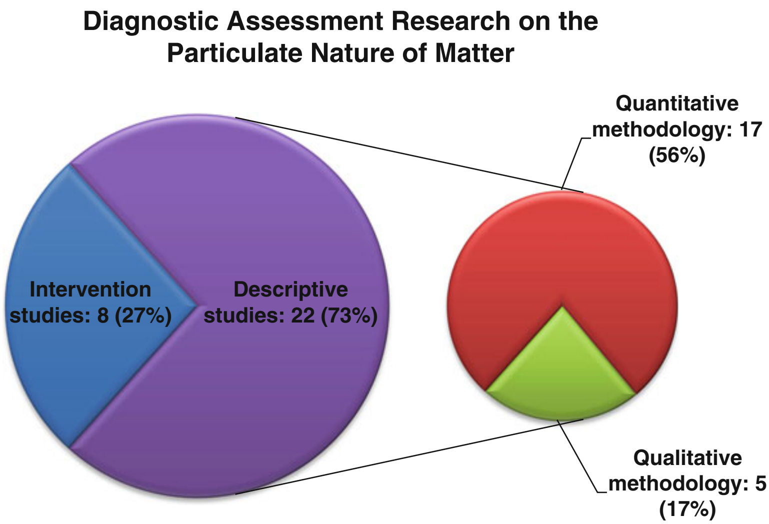


Fig. 1 Diagnostic assessment of particulate nature of matter understandings by research design and methodology

Descriptive Research

A large body of research on student understanding of the particulate nature of matter was conducted to explore students' ways of conceptualizing various particle ideas. Known as the most common descriptive methodology (Fraenkel and Wallen 2003), surveys in these studies were predominantly used to assess student understanding and to find out a range and frequency of misconceptions, adopting a quantitative approach (Ayas et al. 2010; Boz 2006; Devetak et al. 2009; Gabel et al. 1987; García-Franco and Taber 2009; Gomez et al. 2006; Griffiths and Preston 1992; Kahveci 2009; Kahveci and Özalp 2009; Novick and Nussbaum 1978, 1981; Nyachwaya et al. 2011; Odom and Barrow 1995; Othman et al. 2008; Stains 2007; Treagust et al. 2010). Written questionnaires and interviews comprised the means of data collection.

A second line of descriptive research is qualitative, or interpretive, in nature. In these studies the purpose was to understand as well as discursively reconstruct students' conceptions and mental models about the particulate nature of matter, while the focus was on the students' points of view (Adbo and Taber 2009; Nakhleh and Samarapungavan 1999; Nakhleh et al. 2005; Nicoll 2003; Taber and García-Franco 2010). In these studies, semi-structured as well as task- or phenomenon-based in-depth interviews were conducted with individual students. In the following sections, research in the two domains is described with a closer look at each of the studies and the methodologies employed.

Phenomenon No. 2
Two colorless liquids were presented in two stoppered flasks. The first (concentrated ammonia) was opened and a strip of orange paper was held at its mouth. The strip turned blue. The first flask was closed, the second (concentrated hydrochloric acid) opened, and the strip held at its mouth. The strip turned red (Fig. 2(b)).
Tasks:
(5) "Explain why the paper turned blue over the first flask and red over the second flask. Make a sketch."
(6) "How does the substance rise from the liquid to the paper?"

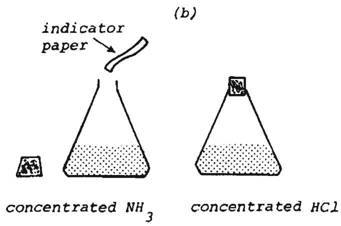


Fig. 2 One of the phenomena used in the interview study by Novick and Nussbaum (1978) (© 1978 John Wiley & Sons, Inc.)

Quantitative Methodology Approach

The research on student misconceptions of the particulate nature of matter appears to be pioneered by Novick and Nussbaum, with studies published in 1978 and 1981. In their earlier work, Novick and Nussbaum (1978) used Piaget-type interviews to investigate how eighth grade students conceptualized the particulate nature of matter. The interviews were concerned with the particle model of the gaseous state of matter and included three phenomena and a total of eight tasks (Phenomenon No. 2 is given in Fig. 2).

In their later study, Novick and Nussbaum (1981) aimed to explore student conceptions of the particulate nature of matter in the gaseous state. Their target was a wider sample of students; thus, they developed a paper-and-pencil instrument called the Test About Particles in a Gas (TAP). The test involved nine items based on phenomena, a simple experiment, or a situation for which the students were required to complete drawings, write explanations, or choose among given drawings or explanations. The tasks were primarily chosen from or built upon the tasks used in their interview study (Novick and Nussbaum 1978). The test was completed by a total of 576 elementary school (grades 5 and 6), junior high school (grades 7, 8, and 9), senior high school (grades 10, 11, and 12), and university sophomore non-science major students.

In a later work, Gabel et al. (1987) explored 90 prospective elementary teachers' views of the particulate nature of matter via a 14-item inventory. Developed by the researchers, the Nature of Matter Inventory was composed of test items with pictures of particles in matter. The respondents were asked to draw pictures of particles after a physical or chemical change occurred (no exemplary items are available for this inventory). The drawings were scored based on the following nine attributes that the students were expected to consider: conservation of particles, proximity of particles, orderliness of particle arrangement, location of particles in container, constancy of particle size and shape, particle discreteness, chemical composition, arrangement of products, and bonding.

Two more recent survey studies with paper-and-pencil testing procedures were conducted in Turkey to investigate student understanding of the particulate nature of matter in relatively large samples. Boz (2006) surveyed 300 students aged 12–18 via a six-item open-ended questionnaire concerned with student understanding of phase changes on particulate level. On the other hand, Ayas et al. (2010) probed secondary and tertiary level students' understanding of the topic by using a questionnaire composed of five open-ended questions. 102 of the students were high school, and 64 were undergraduate freshmen or sophomore chemistry students. In both studies, follow-up interviews were conducted with a subsample of respondent students.

One of the questions in Boz's instrument (Question 1) required knowledge, while the rest required explanations of given phenomena. Question 1 was designed to evaluate student knowledge of the arrangement and motion of particles as well as the strength of the forces between the particles in the three states of matter. Two of the explanatory questions included no mention of the particle model, and three of the questions involved hints to guide student thinking in terms of the particulate nature of matter [i.e., "Question 4: Is there a difference, in terms of particles, between two samples of water at 10 °C and 90 °C? Please explain." (p. 205)]. Likewise, the questions in Ayas et al.'s (2010) instrument were phenomenon based and of explanatory nature with specific referral to the particulate nature of matter [i.e., "Item 3: A jar is filled with ice cubes; the lid is screwed on tightly. The exterior of the jar is dried with a towel. After 20 min, the exterior of the jar becomes wet. How can you explain this situation? Where did the water come from?" (p. 174)].

In their recent work, Treagust et al. (2010) developed the Kinetic Particle Theory Instrument (KPTI) consisting of 11 multiple-choice items requiring understanding in three key conceptual categories related with the kinetic particle theory. These areas were intermolecular spacing in solids, liquids, and gases; effect of intermolecular forces on changes of state; and diffusion in liquids and gases. In responding to the items, following their choice selection, the students were required to write their justification for the particular selection (a sample item is shown in Fig. 3). The instrument was administered to a total of 148 students (in the age range 14–16) in four different countries.

Devetak et al. (2009), in their mixed methodology descriptive research, investigated the level of students' understanding of the solution concentration and the process of dissolving ionic and molecular crystals at particulate level. The participant sample consisted of 408 secondary school students. The researchers used a paper-and-pencil chemical knowledge (CK) test requiring students to draw submicrorepresentations (SMRs) to illustrate their ideas. The researchers also conducted follow-up semi-structured interviews that probed deeper into the students' responses to the test. The CK test consisted of 19 items covering the following topics: pure substances, mixtures, chemical reactions, aqueous solutions, and electrolyte chemistry (Fig. 4 shows one of the items on solution chemistry). The items required student understanding of matter at submicro level and of the relationship between submicro and symbolic, between submicro and macro, and among all three levels.

Item 4. The diagram shows a coloured gas being compressed in a gas syringe until the plunger could not be pushed any further.
The experiment was repeated using the same volume of a coloured liquid.

It was found that the final volume of the gas was:
A. much less than that of the liquid.
B. much greater than that of the liquid.

The reason for my choice of answer is:
……………………………………………………………………………………………….........................
………...

Fig. 3 Item 4 in the Kinetic Particle Theory Instrument developed by Treagust et al. (2010) (With kind permission from Springer Science+Business Media: Treagust et al. 2010, electronic supplementary material, © National Science Council, Taiwan 2009)

In both beakers is the same volume of water. Substance X is dissolved in the water. The volume of the solution formed is unchanged. Draw the solution at particulate level in such a way that a solute particle is presented as •. Water molecules could be omitted for clarity.

a) In a part of the solution represented in the scheme are six molecules of solute.	b) The solution represented in the scheme is two-times more concentrated than the solution in scheme a).	c) The solution represented in the scheme is one third of the concentration of the solution in scheme b).

Fig. 4 Problem No. 9 in the Chemical Knowledge (CK) test developed by Devetak et al. (2009) (With kind permission from Springer Science+Business Media: Devetak et al. 2009, p. 176, © Springer Science+Business Media B.V. 2007)

In another mixed methodology study, Stains (2007) examined the patterns of reasoning used by novice undergraduate chemistry students to classify chemical substances based on their particulate representations. The researcher collected data via both quantitative and qualitative research instruments, which were a Classification Task Questionnaire and interviews, respectively. The Classification Task Questionnaire involved 20 particulate images of various substances. In the images atoms were represented as circles of various colors (with + or – signs added in case of ions). These images were projected onto a large screen one by one for 15-s intervals, and the students were asked to classify them as elements, compounds, or mixtures. For this purpose, the students were provided an answer sheet on which they could check the category to which they believed the projected image belonged. Some of the students were then involved in follow-up semi-structured interviews.

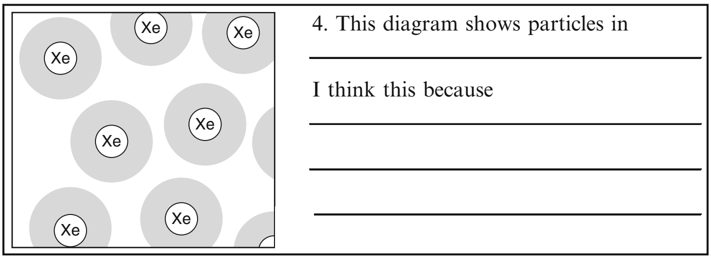


Fig. 5 A sample item from the "Elements, compounds or mixtures? (1)" probe in Taber (2002) (Reproduced by permission of The Royal Society of Chemistry)

The researcher developed three types of interview protocols, and the students were randomly assigned to one. During all of the interviews, the students were asked to draw submicroscopic representations of an element, a compound, and a mixture as well as to construct a concept map about these. In two of the interview protocols (Protocols A and C), the students were constrained by having to classify the particulate images as elements, compounds, or mixtures, while in the third protocol (Protocol B), they were encouraged to self-define their groups (see Appendix A for the first two questions in Protocol B).

Similarly, as part of a larger research, Kahveci (2009) explored chemistry teacher candidates' understanding of the particulate nature of matter through classification tasks of matter as element, compound, and mixture. The classification tasks were adopted from the classroom resources in Taber (2002). The probe entitled "Elements, compounds or mixtures? (1)" starts by asking the respondents to explain in their own words what an element, a compound, and a mixture mean. Following are six diagrams of particulate representations of samples of materials requiring the respondents to decide whether each diagram represents an element, a compound, or a mixture and to explain their reasons in the spaces provided next to each diagram (Fig. 5 shows an item from this probe).

An alternative diagnostic tool for assessing student understanding of the particulate nature of matter was developed and used at college level (Nyachwaya et al. 2011). Arguing that a diagnostic tool should be organized around specific chemistry concepts in order to probe student understanding in depth, the researchers developed an open-ended drawing tool. The tool was composed of three questions that required students to draw particulate representations of chemical reactions involving covalent compounds, ionic compounds, or both (an example question is given in Fig. 6). The purpose of the open-ended assessment was to obtain richer information on students' conceptions of the particulate nature of matter and to identify possible misconceptions.

Gomez et al. (2006) utilized structured task-based interview protocols to examine student conceptions about the particulate nature of matter in a wide age range of 9–22. A distinctive aspect of this study was the researchers' goal of illuminating the degree of coherence in the students' responses. To achieve this goal, Gomez and colleagues incorporated different methodological strategies in their questionnaire.

Question 2. Silver nitrate ($AgNO_3$) reacts with calcium chloride ($CaCl_2$) to form silver chloride (AgCl) and calcium nitrate ($Ca(NO_3)_2$). The reaction is represented by the *unbalanced* chemical equation below:

$$\_\_ \ AgNO_{3(aq)} + \_\_ \ CaCl_{2(aq)} \rightarrow \_\_ \ AgCl_{(s)} + \_\_ \ Ca(NO_3)_{2(aq)}$$

a. Write the appropriate numbers in the blanks to balance the chemical equation

b. In the space below, draw diagrams that represent what you think you might see if you were able to see the atoms, molecules or ions involved in the chemical equation above, Remember to draw the correct number of atoms, molecules or ions of each reactant and each product.

Fig. 6 Example question from Nyachwaya et al.'s (2011) diagnostic drawing tool (Reproduced in part from Nyachwaya et al. (2011), with permission of The Royal Society of Chemistry. http://dx.doi.org/10.1039/C1RP90017J)

The questionnaire was composed of three tasks, each of which was designed based on two strategies, confrontation and contextual variation (Task 2 is provided in Appendix B). The confrontation strategy involved a prediction stage, where the student was expected to predict possible outcomes for a physical fact or event, and a confrontation stage, where an experiment was conducted and the results confronted with the student's predictions. The contextual variation strategy consisted of presenting different physical situations for the same topic. Student responses to the task questions were evaluated for their coherence against the specific criteria of repetition, generalization, and adaptation. Gomez et al. (2006) were primarily inspired by Piaget's model of cognitive organization and reorganization as well as Piagetian theorists' basic instructional principles, one of which is making students aware of conflicts and inconsistencies in their thinking (Driscoll 2000).

In their interview study, Griffiths and Preston (1992) probed grade 12 students' understanding of the concepts atom and molecule. The researchers constructed a detailed interview guide which included two major sections. In the first section, there were questions about the structure, composition, size, shape, weight, bonding, and energy of molecules asked based on a water molecule. In the second section, there were questions about the structure, shape, size, weight, and perceived animism of atoms (the second section is provided in Appendix C). The students were expected to provide answers both verbally and by drawing.

Qualitative Methodology Approach

One of the earliest and most comprehensive studies on elementary school children's (aged 7–10) conceptions about the particulate nature of matter was conducted by Nakhleh and Samarapungavan (1999). The researchers constructed an interview guide consisting of three sequences. The first sequence was composed of questions about properties of pure substances (refer to Fig. 7 for Sequence I), while the second sequence was developed to investigate student knowledge about relationships between particles. The last sequence probed for understanding of phase changes and processes of pure substances. The questions were of either descriptive or

Sequence I. Properties of pure substances (elements or compounds).

1. SHOW: A sugar cube.
2. ASK: This is a sugar cube. Please describe the qualities of this sugar cube.

    IF macro or continuous description
    THEN ASK   What is it made of?
    Is it just one big piece of material?
    Is it made of little bits?
    IF particulate description
    THEN ASK   Think of the smallest bits. Are all of the bits the same or are some different?
    Here is some Play Dough. Please use the Play Dough to help explain what you mean.
    IF particulate, but still not specific
    THEN ASK   Please tell me what these little bits look like?
    What shape are they?
    IF participant cannot get to micro level but remains continuous or macro
    THEN GO ON with interview.
3. REPEAT: Repeat sequence using wood, liquid water, a metal like Cu wire, and a clear balloon filled with He.

Fig. 7 The first sequence in the "Interview for Children's Beliefs about Matter" by Nakhleh and Samarapungavan (1999) (© 1999 John Wiley & Sons, Inc.)

explanatory nature and were designed to elicit understanding on both macroscopic and submicroscopic levels. The descriptive questions asked students to describe substances, and the explanatory questions required explanations of given phenomena. The researchers used the same interview guide in a later study on investigating middle school students' conceptions of the particulate nature of matter (Nakhleh et al. 2005).

A later study by Nicoll (2003) was conducted "to determine how undergraduate students represented the submicroscopic world in a free-form format" (p. 205). A total of 56 students were individually involved in semi-structured, hour-long interviews. The interview protocol included two questions, the first of which required the students to draw the Lewis dot structure of a molecule given in symbolic form. For the second question, the students were provided with modeling clay (Play-Doh) and sticks to build a stick and ball model for the same molecule. During the interviews, the students were asked to explain their models and their reasoning while building the molecule. The researcher developed a coding scheme to unravel the different ways that the students used to model the molecule. This scheme consisted of five main areas: arrangement, color, geometry, size, and sticks. Variable in each of these areas, the students were reported to build quite diverse molecular models.

In their qualitative work to understand 16-year-old Swedish students' mental models of matter at the particle level, Adbo and Taber (2009) used semi-structured interviews along with students' own drawings of the atom and the different states of matter. The students participating in the interviews were enrolled in the science program at upper secondary level in two different schools. Each student participated in three sessions of interviews. In the first session, the students were asked to draw their image of an atom, and the conversation that followed was based on the drawing. Follow-up questions were asked to illuminate students' mental models of subatomic particles, electrostatic interactions, and particle motion. The subsequent two interviews were conducted about the different phases of substances. For instance, the students were asked to draw an image of a solid, and then questions such as "Why is a solid, solid, a liquid, liquid, and a gas, a gas?" and "What is the difference between the three phases?" were asked (p. 767).

In the interpretive study conducted by Taber and García-Franco (2010), the researchers utilized an *inclusive cognitive resources* or *knowledge in pieces* perspective that focused on understanding implicit knowledge elements that are activated when students consider chemical phenomena. Data analysis in this study attended to the way students built their explanations as an amalgam of intuitive notions and taught science concepts. Another round of data analysis was concerned with the extent to which student explanations were in harmony with the target particle ideas as presented in the English National Curriculum, the results of which are reported in García-Franco and Taber (2009).

In their research, Taber and García-Franco used semi-structured interviews about instances and interviews about events (White and Gunstone 1992) to understand student explanations in depth. The participating students were enrolled in English secondary schools and in the age range 11–16. Thus, the interviews were phenomenon based. A collection of 14 different phenomena related to the particulate nature of matter commonly taught in schools represented the instances or the events. In interviewing about events, most of the phenomena were demonstrated, and some, such as the spreading of smells and floating of ice on water, were raised as thought experiments. The two main questions that guided the interviews were "Can you describe what you are seeing?" and "Can you explain why things happen that way?" The students were also asked to make a sketch that could help clarify what they were saying (García-Franco, March 1, 2011, personal communication).

Intervention Research

Based on the review of the related literature, intervention studies in the content area of the particulate nature of matter appear to focus on the implementation of particular teaching methods (Adadan 2006; Gabel 1993; Treagust et al. 2011; Yezierski and Birk 2006a), new curricula or teaching program (Chandrasegaran et al. 2008; Lee et al. 1993; Margel et al. 2008), or teacher education activities (Kokkotas et al. 1998). Six of the studies were conducted following pretest-posttest design, and two (Chandrasegaran et al. 2008; Gabel 1993) were based on posttest-only control group design. The research participants ranged from sixth grade students to preservice science teachers, and the data collection tools varied from paper-and-pencil multiple-choice questions to face-to-face semi-structured interviews.

Yezierski and Birk (2006a) utilized a multiple-choice instrument to assess the effects of a teaching intervention (computer animations) on students' conceptions of the particulate nature of matter. The participants of the study were eighth grade middle school students as well as 10th, 11th, and 12th grade high school chemistry

Question 19. A water molecule in the liquid phase is _______ a water molecule in the solid phase.		
A. smaller than	B. lighter than	C. heavier than
D. larger than	E. the same weight as	

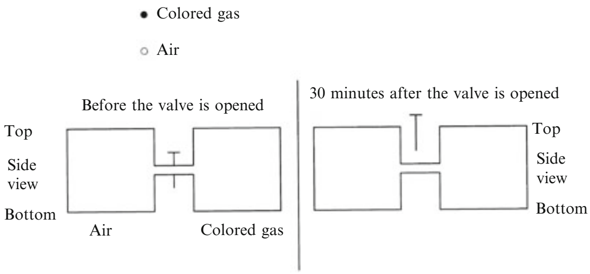
Fig. 8 A sample question from the ParNoMA instrument (Reprinted (adapted) with permission from Yezierski and Birk (2006b). Copyright 2006 American Chemical Society)

students and college general chemistry students. The 20-item instrument, Particulate Nature of Matter Assessment (ParNoMA), was validated by three general chemistry instructors and two general chemistry teaching assistants. The test involved distractors based on previously known student misconceptions in the following topics: size of particles, weight of particles, phases and phase changes, composition of particles, and energy of particles (a sample question is given in Fig. 8). Three of the questions included diagrams representing particles of matter in different states. Two of the questions included particulate drawings with no relation to a container. In one of the questions, a container was drawn; however, specific care was taken so that the scales were not mixed. In the diagram, particulate views of molecules were drawn into callout circles connected with lines to the container, meaning that the particles represent an enlarged view of the container's contents. Built up of easy-to-score multiple-choice questions, the ParNoMA instrument is a relatively feasible tool for use by practicing teachers.

In a recent study conducted by Adadan (2006), the effect of multirepresentational instruction on 11th grade introductory chemistry students' conceptual pathways of the particulate nature of matter was explored. The researcher constructed and used a ten-item open-ended questionnaire, entitled the Nature of Matter Diagnostic Questions (NMDQ) as pretest, posttest, and delayed posttest. The questions comprised of different tasks that included pictorial particulate representations and sought students' explanations and drawings of the given phenomena (a sample item is shown in Fig. 9). The focus and content of the tasks in the questionnaire were related to the following topics: particle motion, phases and phase change, dissolution, diffusion, and compressibility. The researcher also conducted interviews with a carefully selected sample of students for a follow-up on their responses to the questionnaire.

In their 2-year longitudinal study, Lee et al. (1993) first analyzed sixth grade middle school students' common misconceptions about matter and molecules then revized the curriculum unit "matter and molecules" and compared the effectiveness of the earlier and revized version of the curriculum material on students' understanding of the topic. The researchers developed two types of instruments: a paper-and-pencil test and clinical interview protocols. The paper-and-pencil test included 26 questions in multiple-choice and short-essay formats, concerned with a number of key conceptions of the kinetic molecular theory. The majority of the questions asked for explanations of physical phenomena (i.e., explanation of how the smell of a freshly cut onion reaches peoples' noses shortly), and some of the questions

Question 6
Particles of air and particles of a colored gas are placed in a container, which is separated by a valve. Before the valve is opened the two gases are kept separate in the container. Then, the valve is opened. Use **solid** circles to represent colored gas particles and **open** circles to represent air particles. Like this:



a) What happens after the valve is opened? **The explanation is as important as your drawings.**
b) What property of gas particles accounts for what happens after the valve is opened?

Fig. 9 A sample question from the NMDQ instrument utilized in the Adadan (2006) study (Reproduced by permission of author)

required knowledge (i.e., if the air was made of molecules). The students' were also probed for their understanding of the nature of matter both at the macroscopic and submicroscopic levels such as predicting the arrangement of particles in given substances (i.e., iron).

Lee and colleagues also developed a structured interview protocol allowing the interviewers to follow a standard procedure. Like the paper-and-pencil test, the protocol was developed for the sixth grade students and required them to describe, predict, and explain natural phenomena. The protocol included five major tasks, which were concerned with (a) the nature of matter and the three states of matter, (b) expansion and compression of gases, (c) changes of state, (d) dissolving, and (e) thermal expansion (see Fig. 10 for an excerpt from the interview protocol). The interviews allowed the researchers to probe into student thinking more in depth.

Another longitudinal study on junior high school students' (grades 7–9) conceptions of the structure of matter was conducted by Margel et al. (2008). Adopting a quasi-experimental approach, the researchers investigated how students' conceptions changed over a 3-year period of time, while a new instructional approach dealing with "Materials" had been implemented. Data were collected from 1,082 students five times during the 3-year period via a questionnaire, which required the students to draw structures of materials as if they looked from a very powerful magnifying instrument. They also were required to write explanations. The materials belonged to two groups: one group included familiar materials that had been discussed in class (i.e., iron, water, nylon), and the other group involved unfamiliar materials such as juice and wool. In this way, the researchers' goal was to understand if the students were able to generalize and transfer their knowledge to new situations, and the questionnaire gave the students the opportunity to express their knowledge in both verbal and visual ways. The questionnaire (given in Fig. 11) has

Task 1–3	Questions	Commentary	Goal Conceptions
Nature of gas (air)	O: What is air? P1: (If the student says there is nothing in the air) Wave your arm in the air. Do you feel anything? Is anything striking your arm? What is it? P2: Suppose you are ableto see air with magic eyeglasses. What is air made of? (What is in the air?) P3: Draw a picture of what you would see? P4: (If the student draws dots, waves, etc.) What are these dots (waves, etc.)? Are they all the same? What is between them? Are they moving? If so, are they always moving? P5: (If student mentions molecules) Is air a mixture? What does that mean? Is air made of different molecules?	Whether students think in terms of empty spaces and constant motion of molecules (waves, chunks, etc.), and Purposes: To determine (1) students' conceptions of air, (2) student's microscopic view of gases (air), liquids, and solids, (3) (4) whether students understand that the empty space and motion vary in solids, liquids, and gases (air).	9, 10, 11, 12, 16, 17 [based on 19 target conceptions –eight macroscopic, 11 sub-microscopic-identified by the authors]

Fig. 10 Excerpt from the clinical interview protocol developed by Lee et al. (1993) (© 1993 John Wiley & Sons, Inc.)

Consider the following materials:

Iron, Water , Air, Nylon, Juice, Wool, Oxygen, and Paper.

Describe in words and draw the structure of these materials as if you were using a magnifying instrument. very powerful

Explanations ***Drawings***

Iron

____

____

Water

____

____

Fig. 11 The questionnaire used in the longitudinal study by Margel et al. (2008) (© 2007 Wiley Periodicals, Inc.)

an easily modifiable structure as in different studies the samples of materials may be replaced with others to fit specific curricular contexts.

The study by Gabel (1993) involved three classes of 66 high school students in total, two of them assigned as treatment groups and one as control groups. The treatment groups were exposed to teaching, which particularly focused on the particulate nature of matter. The purpose was to determine whether there was difference in achievement between the groups on each of the three levels of symbolic, submicroscopic, and macroscopic representations of chemical symbols or phenomena. Test items on each level were developed resulting in a triad for 25 different areas, with

75 items in total (no exemplary items are available for this test). The items were administered to the students during the school year as part of their unit tests.

Exceptional to research carried out with students in primary and secondary grades, Kokkotas et al. (1998) worked with prospective science teachers to improve their knowledge of the particulate nature of matter and help them adopt a more constructivist approach to science teaching. As a methodology, the researchers first surveyed primary school pupils' ideas on the properties of matter and changes of state (with seven open-ended questions) and then confronted the prospective teachers in their sample with the pupils' responses. The teachers were asked to evaluate the students' answers as if they were their actual teachers. Then, they were involved in a 4-week workshop where they had the chance to work in groups, reflect on the pupils' and their own misconceptions, and discuss possible teaching interventions to help students overcome their conceptual obstacles. Following the workshop the prospective teachers were given the same evaluation task in reworded form as a posttest. The strategy used in this study to investigate prospective teachers' understanding of the particulate nature of matter is unique in the sense that real data from students in the same context were used and that the teachers were confronted with both students' and their own misconceptions. In this way, the teachers were allowed to create a conceptual empathy with students. An example question from the pretest in this study is given in Appendix D.

Two-Tiered Assessment

While interviewing has proven to be a very useful method to assess student conceptions, it is a method that is time-consuming and requires training. According to Treagust (1988), a more convenient way for a classroom teacher to identify student misconceptions is to administer a pencil-and-paper test with incorporated misconceptions in a content area. Introducing these tests as *diagnostic tests* to the field, Treagust (1988) proposed a two-tier item development methodology, which includes three broad stages: defining the content, obtaining information about students' misconceptions, and development of the two-tier test items.

To date, numerous studies in the different subjects of chemistry concerned the development and use of two-tier diagnostic test items as described by Treagust. Some of these include the Test to Identify Student Conceptualizations (TISC) (Voska and Heikkinen 2000) and the Test to Identify Students' Alternative Conceptions (TISAC) (Özmen 2008) in chemical equilibrium, Qualitative Analysis Diagnostic Instrument (QADI) in inorganic chemistry (Tan et al. 2002), and the Ionization Energy Diagnostic Instrument (Tan et al. 2008).

Conducted for the review in this chapter, a specified Web of Knowledge search on two-tiered assessment of the particulate nature of matter conceptions yielded seven results. Of these publications, five were retained for inclusion. Chiu's longitudinal research exploring more than 10,000 Taiwanese students' chemistry conceptions was excluded from the analysis as it targets a large base of chemistry

Item 3. As the difference in concentration between two areas increases, the rate of diffusion: a. decreases b. increases The reason for my answer is because: a. there is less room for the particles to move. b. if the concentration is high enough, the particles will spread less and the rate will be slowed. c. the molecules want to spread out. d. the greater likelihood of random motion into other regions.

Fig. 12 A sample item from the diffusion and osmosis diagnostic instrument developed by Odom and Barrow (1995) (© 1995 John Wiley & Sons, Inc.)

concepts – including particle ideas – at different grade levels (Chiu 2007). A different study on curriculum development in Namibia was also left out.

One of the studies retained is a work on investigating the relationship between student understanding of the particulate nature of matter and chemical bonding conducted by Othman et al. (2008). The other is a research (Odom and Barrow 1995) conducted in the biology field exploring students' understanding of diffusion and osmosis. Chandrasegaran et al.'s (2008) study is an evaluation study of a teaching program designed to enhance student understanding of changes at particle level during chemical reactions. One of the two most recent studies (Treagust et al. 2011) is also an evaluation of an instructional program designed to improve students' understanding of particle theory concepts. In another study (Liang et al. 2011), the researchers examine student conceptions of the behavior of gas particles.

In addition to the studies found through the Web of Knowledge databases search, the author's two subsequent studies communicated in an annual science education conference (Kahveci and Özalp 2009; Özalp and Kahveci 2009) were also included in the pool. Of all the two-tiered assessment studies, five are descriptive with quantitative methodology (Kahveci and Özalp 2009; Liang et al. 2011; Odom and Barrow 1995; Othman et al. 2008; Özalp and Kahveci 2009) and two are intervention studies (Chandrasegaran et al. 2008; Treagust et al. 2011). Based on this pool, the two-tiered assessment research comprises 29 % of the descriptive studies with quantitative methodology, 25 % of the intervention studies, and 23 % of all diagnostic assessment work in the content area of the particulate nature of matter.

Following the procedure described by Treagust (1988), Othman and colleagues (2008) developed a two-tier multiple-choice diagnostic instrument consisting of ten items, in which each set of five items was designed to assess each of the two concepts. The items concerning the particulate nature of matter were related to phase changes, dissolving, and conservation of matter (the first two items are given in Appendix E). The ten-item instrument was administered to 260 students (15–16 years old) attending grades 9 and 10 of a secondary school in Singapore.

Odom and Barrow (1995) were concerned with the development and application of a 12-item two-tier diagnostic test measuring college biology students' understanding of diffusion and osmosis. The instrument was administered to 240 students enrolled in a college freshman biology laboratory course. In this study, the conceptual knowledge examined included the particulate and random nature of matter in the context of diffusion and osmosis processes (Fig. 12 includes a sample item).

Item 6. A liquid substance takes the shape of its container. Based on this information:
The shape of water molecules changes depending on the shape of the container.
A) True B) False
Reason:
1. As water molecules are solid, their shape does not change.
2. Water molecules are elastic.
3. No matter what the shape of the container is, the shape of the molecules does not change.
4. Water molecules are in the form of water drops.
5. None. My reason:

Fig. 13 A two-tier item from the diagnostic instrument developed by Özalp and Kahveci (2009) (Reproduced by permission of author)

The present author's research involved the development of a diagnostic instrument to assess middle and secondary Turkish students' conceptions in the topic of the particulate nature of matter (Kahveci and Özalp 2009; Özalp and Kahveci 2009). The focus was on portraying the ontological bases of student misconceptions as available in the literature and incorporating those in the distractors of the items. Aligned with content in the middle school curricula, an assessment instrument of 25 distractor-driven, multiple-choice items, 15 of which were two-tiered, was constructed (an exemplar two-tier item is given in Fig. 13). Employing cross-sectional survey methodology, data were collected from a randomly selected sample of 696 students attending primary and secondary schools (grades 6–11).

Liang and colleagues (2011) developed six two-tier test items by using dynamic representations to diagnose eighth and ninth grade students' mental models of the behavior of gas particles. The research was conducted in Taiwan. Due to the nature of the items, the students completed the test work on a computer (screenshots of a sample test item are provided in Appendix F). Besides exploring the characteristics of students' mental models, the researchers wanted to know if students change their mental models when they are exposed to similar problems with different representations.

The two intervention studies based on two-tiered assessment were evaluations of teaching programs. Chandrasegaran et al. (2008) designed an intervention program introducing seven types of chemical reactions with particular emphasis on the use of multiple levels of representation (macroscopic, submicroscopic, symbolic). To assess the efficacy of the program, Chandrasegaran and colleagues administered their previously developed 15-item *Representational Systems and Chemical Reactions Diagnostic Instrument* (RSCRDI) to both experimental and control group ninth graders in Singapore. An example item from the RSCRDI is given in Fig. 14.

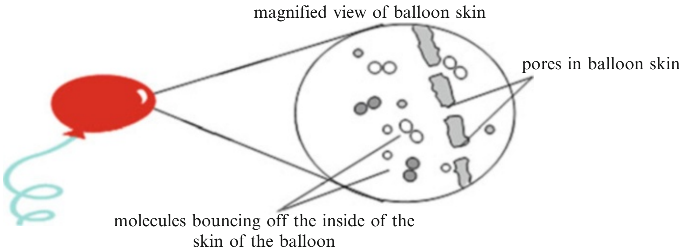
In their study conducted in Malaysia, Treagust and colleagues (2011) aimed to evaluate the efficacy of an intervention program designed to teach particle theory concepts to high school, undergraduate, and postgraduate students from six educational levels. The researchers used their previously developed 11-item Particle Theory Diagnostic Instrument (PTDI) in a pretest-posttest design. The instrument was designed to evaluate understanding about intermolecular spacing, the influence of intermolecular forces on change of states, and diffusion in liquids and gases (a sample item is shown in Fig. 15).

Item 8. Equal volumes of dilute nitric acid and aqueous sodium hydroxide having the same concentration are mixed together. The resulting mixture remains colourless, but becomes warmer. It may be concluded that
A. the resulting solution is neutral.
B. no chemical change has taken place.
C. the aqueous sodium hydroxide has become more dilute.

*The **reason** for my answer is:*
1. More water molecules are present in the mixture.
2. Na^+ ions and NO_3^- ions and NO ions have reacted together to produce sodium nitrate.
3. The ions in nitric acid and sodium hydroxide are still present at the end of the reaction.
4. An equal number of H^+ ions and OH^- ions have reacted together to produce water molecules.

Fig. 14 A sample item from the Representational Systems and Chemical Reactions Diagnostic Instrument (Chandrasegaran et al. 2008) (With kind permission from Springer Science+Business Media: Chandrasegaran et al. 2008, © Springer Science+Business Media B.V. 2007)

Item 7. A balloon is inflated and tied at the neck to prevent it from deflating. The diagram shows a magnified view of the skin of the balloon and the particles in the inflated balloon.



After several hours, the balloon would be found to remain the same size.
A. True B. False

The reason for my choice of answer is:
1. Air molecules bounce off the skin of the balloon.
2. Air molecules diffuse through the skin of the balloon.
3. Air molecules are smaller than the holes in the balloon skin.
4. Air molecules from the outside enter the balloon through the pores.

Fig. 15 Example of an item in the conceptual category "Diffusion in liquids and gases" in the Particle Theory Diagnostic Instrument (Treagust et al. 2011) (Reproduced in part from Treagust et al. 2011, with permission of The Royal Society of Chemistry. http://dx.doi.org/10.1039/C1RP90030G)

Discussion and Conclusions

The analysis from a research design perspective in this chapter demonstrates that descriptive studies with quantitative methodology approach dominate diagnostic assessment research in the topic particulate nature of matter. The review is limited with the articles in the sample selected by using search criteria described in previous sections; thus, it is not possible to know if this pattern persists over a larger literature base. However, much care was taken to bring together publications that report core research in the area over several decades.

A quantitative methodology approach to research is understood at the paradigm level as an entirely different way of viewing the world. Bogdan and Biklen (1998) distinguish between *methodology* and *methods*, arguing that methodology refers to the worldview or the general theoretical perspective employed in a research study. Methods, on the other hand, are the specific techniques used for data collection (such as interviews).

As a general theoretical perspective, the guiding methodology depends on researchers' worldviews or paradigms, defined as basic set of beliefs guiding actions (Guba and Lincoln 1989). Guba and Lincoln make distinctions between two alternative paradigms: the positivist and the constructivist (or interpretive) paradigms, which deviate on the very basic view of "reality." According to the constructivist paradigm, "truth" is a matter of consensus among informed and sophisticated constructors, not of the correspondence of an objective reality" (p. 44). In more familiar terms, Bogdan and Biklen (1998) refer to these two distinct paradigmatic approaches as qualitative and quantitative approaches to conducting research.

Although it is desirable that methods match methodologies, as also evident from this review, in some instances qualitative methods of data collection have been used alone or as part of mixed methods studies, without drawing away from the quantitative methodology approach (Guba and Lincoln 1989). For example, Gomez et al. (2006) utilized questionnaire-based personal interviews grounded on two strategies with the goal of evaluating the degree of coherence in students' knowledge schemes. In this study, coherence was theoretically defined prior to data collection, and three criteria were used to evaluate student responses. In the interview studies conducted by Griffiths and Preston (1992), García-Franco and Taber (2009), and Novick and Nussbaum (1978), evaluation of student understanding of the particulate nature of matter was carried out based on target scientific conceptions as presented in curricula. On the other hand, in several other mixed methods studies, interviewing was used for triangulation purposes (i.e., Boz 2006; Devetak et al. 2009).

Taber and García-Franco's (2010) work illustrates the extent to which paradigms, or the general theoretical perspective adopted by researchers, may lead to different approaches to data analysis. Using the same data set from their previous study (García-Franco and Taber 2009), in their more recent investigation of intuitive cognitive resources that students use to build explanations of phenomena, the researchers constructed a grounded theory of implicit cognitive resources activated in learning chemistry. Similarly, other researchers constructed frameworks of student descriptions and explanations of the particulate structure of matter and processes such as phase changes and dissolving, as emerging from interviews or other qualitative data (Nakhleh and Samarapungavan 1999; Nakhleh et al. 2005).

Apart from the research design, a closer look into the data collection methods also reveals some distinctions. Part of a qualitative methodology or not, qualitative methods of data collection and associated tools are methods that allow for a deeper exploration of student reasoning potentially responsible for students' ideas. If the purpose of a researcher is to understand how students come to know what they know, either a misconception or not, then qualitative methods such as interviewing are more promising in getting some answers. In such cases, it is important for the researcher to understand students' points of view and experiences through their own words and actions (Maykut and Morehouse 1994). In this case, by using qualitative methods of data collection, the researcher acts as "human-as-instrument" (p. 46).

The bulk of the studies reviewed utilized qualitative methods at least partially. With the exception of the multiple-choice tests developed by Yezierski and Birk (2006a) and by Gabel (1993), the tools utilized in the rest of the studies ranged from open-ended questionnaires to task- or phenomenon-based interviews. Open-ended questions (in short-essay format) requiring explanations of physical phenomena (i.e., condensation or diffusion at particle level) were used fully (Ayas et al. 2010; Boz 2006) or partly (Lee et al. 1993; Novick and Nussbaum 1981) in several of the studies. In another form of open-ended probes, Nyachwaya et al. (2011) asked students to draw the reactant and product particles in given chemical reactions. Drawings were also used as data in the following studies: Margel et al. (2008), where students were asked to draw structures of various materials as if they looked from a very powerful magnifying instrument; Devetak et al. (2009), where students were required to draw submicrorepresentations of solutions; Gabel et al. (1987), where students were asked to draw pictures of particles after a physical or chemical change occurred; Adbo and Taber (2009), where students produced their own drawings of the atom and the different states of matter; and most of the other studies as part of interviews.

In some cases multiple-choice items were coupled with open-ended questions that required explanations for a response choice. For instance, in the computer-based assessment by Liang et al. (2011), the students were expected to write explanations to justify their selected answer. The Kinetic Particle Theory Instrument developed by Treagust et al. (2010) also consisted of items including spaces for writing justifications. Adadan (2006) used task-based questions requiring explanations of physical phenomena such as changes of state. In another task-based questionnaire, Stains (2007) asked students to explain their reasoning while classifying given submicroscopic representations of materials in groups based on their similarities and differences. Similarly, Kahveci (2009) asked preservice chemistry teachers to explain why they would classify a given particulate representation of a substance as element, compound, or mixture based on the probe by Taber (2002).

The two-tiered assessment instruments may be classified in two groups based on their potential of elucidating student reasoning. One group consists of items both tiers of which are composed of provided choices. Being more common, this form of two-tiered testing was employed in the following studies: Odom and Barrow (1995), Othman et al. (2008), Chandrasegaran et al. (2008), and Treagust et al. (2011). The other group involves items the second tier of which includes a free-response choice along with predetermined reasoning statements. This type of two-tier testing was used by Kahveci and Özalp (2009). The latter design of two-tiered items allows students to write their own reasons, if none of the second-tier statements matches their way of thinking.

Several of the studies were structured around phenomenon-based, face-to-face interviewing, which is a method that facilitates elicitation of student ideas and ways of reasoning in a most open way. The interviews ranged from semi-structured to structured, which started with a demonstration of a phenomenon [such as in the

Taber and García-Franco (2009) study], or questions followed with drawings or modeling by using modeling clay [i.e., Adbo and Taber (2009); Nakhleh and Samarapungavan (1999)]. Because the researcher is the data collection instrument in qualitative inquiries, interviewing is an adaptable method in the sense that follow-up questions emerge based on participants' preceding responses or comments (Guba and Lincoln 1989).

The review illuminates some potential areas for further research. Despite the enormous body of diagnostic research on student understanding of the particulate nature of matter from a misconceptions perspective, studies of intervention type appear to be in limited number. For over three decades, common patterns have been identified of student thinking in different contexts. Thus, it is possible to say that data saturation in this area has been achieved to a great extent. Also, the available assessment instruments form a potential repository from which it may be possible to adopt appropriate tools. Thus, greater attention needs to focus on the development and evaluation of reform-based science teaching practices, for a more effective teaching and learning of the particulate nature of matter ideas, among other goals of scientific literacy. Diagnostic assessment appears to be a promising evaluation strategy of the efficiency of these methods.

Another area for further research in diagnostic assessment of chemistry learning emerges from the need to connect chemistry education research and practice. In spite of ample research in the domain of diagnostic assessment of particle conceptions and also in the domain of two-tier testing in various chemistry topics, there is need for more work at the intersection. Although not as much as more open-ended methods such as interviewing, two-tiered items have the potential of eliciting students' ways of reasoning more than traditional multiple-choice tests. Moreover, two-tiered diagnostic assessment is a method that has practical power in everyday classroom use. Much of the interviewing research has been conducted by science education researchers; however, an important issue is the transfer of research findings to the everyday life in classrooms for improved science education practices. Practicing teachers overwhelmed with curriculum, textbook, and evaluation demands can more readily use easy-to-implement and easy-to-score two-tiered diagnostic tests instead of interviews. Thus, a route for further research may be the development and use of two-tier instruments focused on particle concepts.

In conclusion, while portraying underlying theoretical perspectives, the review of diagnostic assessment research and methods suggests further actions to be undertaken by both researchers and teachers. The available tools may be adopted for use in particular research and teaching contexts to assess student understanding. In particular, teachers may conduct pre- and post-assessments of student conceptions to evaluate and reflect on the effectiveness of their own teaching practices and make revisions as needed. Researchers in the field may contribute to the growth of diagnostic assessment tools and practices (i.e., two-tier testing) as well as engage in the advancement of teaching strategies and methods concerned with informed understandings of the particulate nature of matter.

Appendices

Appendix A

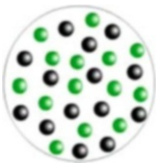
The first two questions in Protocol B from the study by Stains (2007) (Reproduced by permission of author)

Protocol B

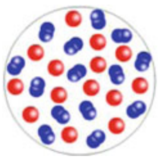
Form B

Composition of Matter

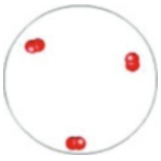
1. Classify the following microscopic representations of materials in groups based on the similarities and differences that you see. Explain your reasoning.



1B

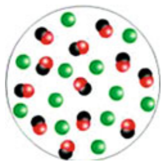


1F

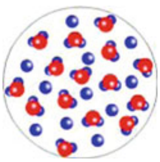


1A

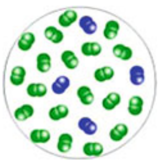
1G



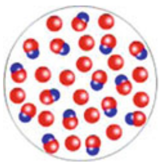
1I



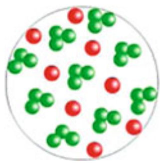
1D



1E



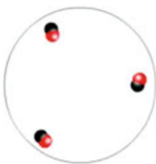
1H



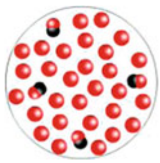
1C

2. Classify the following microscopic representations of materials with the previous set based on the similarities and the differences that you see. Explain your reasoning.

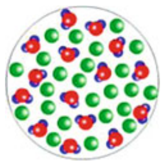
2E



2C



2F



2B

Appendix B

One of the three tasks in the questionnaire of the study by Gomez et al. (2006) (© 2006 Wiley Periodicals, Inc.)

Task 2: Solution of two liquids (alcohol and water) involving a discernible reduction in height

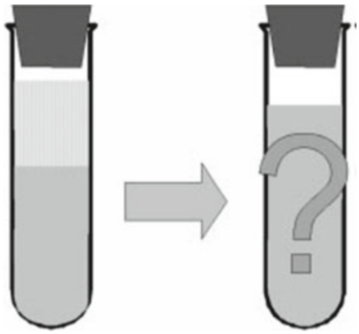


Fig. B.1 How do you explain that the weight has not varied but the height has? (Gomez et al. 2006) (© 2006 Wiley Periodicals, Inc.)

The student is shown a test tube of approximately 80 cm height and 1.5 cm diameter and a bottle of distilled water and another of alcohol. The tube is half filled with water and then, tilting the tube slightly, the alcohol is added in such a way that it runs down the side of the tube. The student marks the level of the liquid by marker pen and the tube is closed with a cork.

Prediction stage. The replies to this task provide the variable L-ANTE (L refers to the height and ANTE refers to replies given before vigorously shaking the liquid). The students are asked to predict what will happen when the tube and contents are shaken vigorously (Questions: Will the quantities of the liquids vary? Will the weight change? Will the height of the liquid change?)

The tube is shaken, inverting it several times until the contents are totally homogenized. The height will be seen to have dropped 1–2 cm, while the principle of mass conservation will be checked (Fig. B.1).

Confrontation stage (L-POST). The student is asked to draw what has happened to the water and alcohol to justify the increased concentration that occurred during mixing (Questions: What has happened? Is it what you thought would happen? How do you explain that the weight hasn't varied while the height has? What would you see inside the tube before and after shaking if you had a powerful microscope?)

Nonrelevant variation. Repeat the process with alcohol and colored water (same sequence of questions as in prediction and confrontation stage).

Appendix C

Questions about atoms from the interview guide by Griffiths and Preston (1992) (© 1992 by the National Association for Research in Science Teaching. Published by John Wiley & Sons, Inc.)

Atoms	
(A)	Structure/shape
	45. If you were to take one atom and look at it under a microscope so powerful that you could see all the details of an atom, what would you see? [Get the students to draw a picture.]
	46. Are there smaller parts which make up atoms? What are they?
	47. Do you think that all atoms would look the same? How would they be different?
	48. Are atoms flat or do they have more than two dimensions? Are they all like this?
	49. Is there anything between atoms? What is it?
(B)	Size
	50. How big are atoms? Try to compare them with something.
	51. How would the size of an atom compare with the size of a molecule?
	52. Are all atoms the same size? Why would they be different?
	53. Can the size of an atom change? If so, when would a change occur?
(C)	Weight
	54. Do all atoms weigh the same? How would you explain the difference in weight between atoms?
	55. How heavy do you think an atom is? Try to compare it with something.
(D)	Animism
	56. Do you think atoms are alive?
	57. Atoms in a pencil appear not to be alive, and atoms in your body appear to be alive. How do you explain the differences?

Appendix D

An example question from the pretest in the study by Kokkotas et al. (1998) (Reprinted by the permission of the publisher (Taylor & Francis Ltd, http://www.tandf.co.uk/journals))

Example from the pretest

Pupils in the 6th grade of primary education were asked to answer a questionnaire to elicit their ideas about the states of matter and their transformations. Pupils replied to the questionnaire 2 months after their last relevant lesson. The pupils' most common answers were collected and assembled along with the question they refer to.

You are asked to act as "real teachers" and evaluate pupils' answers. You can classify pupils' answers in one of the following categories: "correct," "incorrect," "partially correct," "tautology," "irrelevant." Each answer should be put in one category only. Write your evaluation in the box next to each answer.

Question 4: Substances like salt and sugar are dissolved when put in water. How do you explain this?

Pupils' answers:

(1) When sugar is put in water and we stir the water the sugar dissolves.	
(2) These substances are not hard enough to resist dissolving.	
(3) The water has the force to dissolve these materials.	
(4) It's a property of sugar or salt.	
(5) The water absorbs the molecules of sugar or salt.	
(6) When these materials are put in water they split in many tiny parts that you can't see.	
(7) The molecules of the substances are dissolved in the water.	
(8) The sugar or the salt became liquid sugar or liquid salt.	

Appendix E

Items 1 and 2 in the Particulate Nature of Matter and Chemical Bonding Diagnostic Instrument (Othman et al. 2008) (Reproduced by permission of author)

1. Assume a beaker of pure water has been boiling for 30 min. What is/are in the bubbles in the boiling water?

A. Air
B. Oxygen gas and hydrogen gas
C. Oxygen
D. Water vapour (water in the gaseous state)
E. Heat

Reason:

(a) The hydrogen and oxygen atoms in water molecules break away from each other to form gases.
(b) Heating gives the particles more energy, and they are able to break away from their attractions. As the particles break apart, the air between the particles is released in the form of bubbles.
(c) Heat energy is absorbed by the water and released as bubbles.
(d) The forces between the water molecules are overcome, and the water molecules break free from the liquid to form steam.
(e) Oxygen dissolved in water is expelled as air bubbles.

2. A 1.0 g sample of solid iodine is placed in a tube and the tube is sealed after all of the air is removed. The total mass of the tube and the solid iodine is 27.0 g.

The tube is then heated until all of the iodine evaporates, and the tube is filled with iodine gas. The mass after heating will be:

A. less than 27.0 g
B. 27.0 g
C. more than 27.0 g

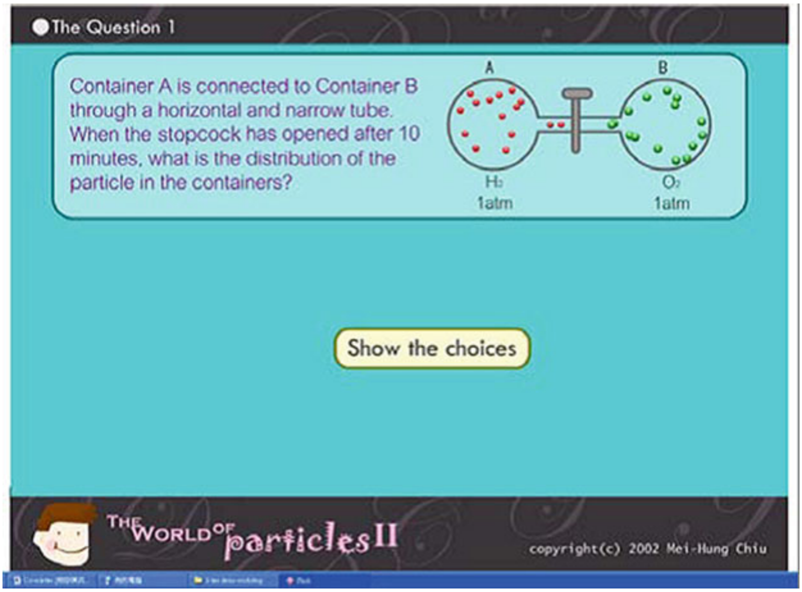
Reason:

(a) A gas weighs less than a solid.
(b) Mass is conserved.
(c) The particles become more spread out when the iodine becomes a gas.
(d) Iodine gas is lighter than air.

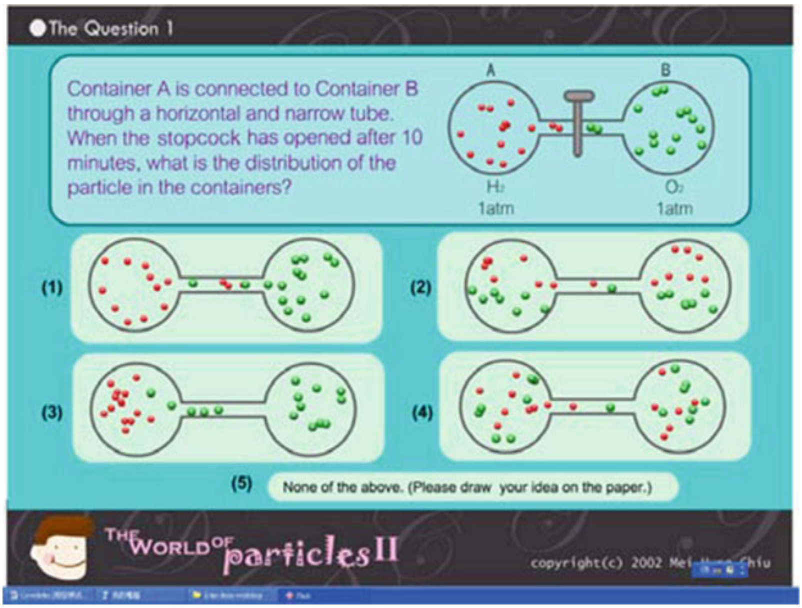
Appendix F

Screenshots of Question 1 in the computer-based diagnostic test on gas particles (Reproduced in part from Liang et al. (2011) with permission of The Royal Society of Chemistry. http://dx.doi.org/10.1039/C1RP90029C)

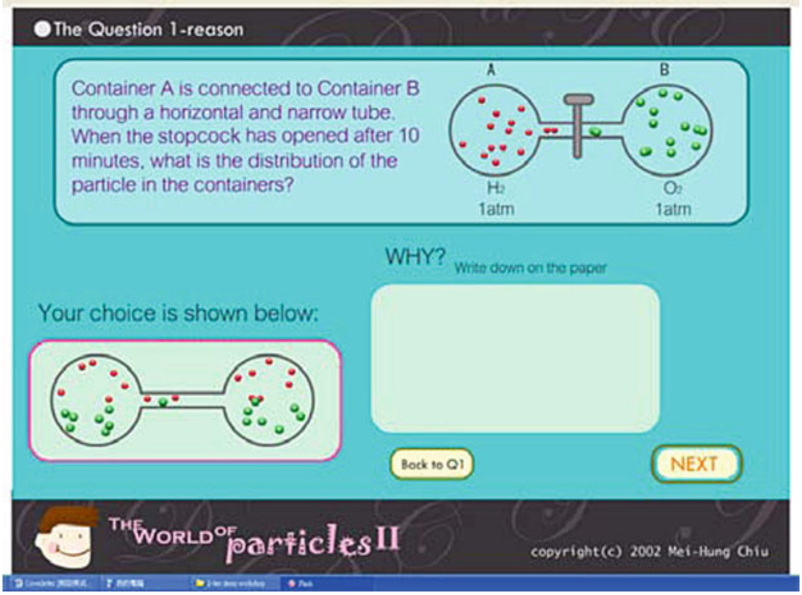
Step 1



Step 2



Step 3



References

Adadan, E. (2006). *Promoting high school students' conceptual understandings of the particulate nature of matter through multiple representations.* Doctor of Philosophy dissertation, The Ohio State University, Columbus.

Adbo, K., & Taber, K. S. (2009). Learners' mental models of the particle nature of matter: A study of 16-year-old Swedish science students. *International Journal of Science Education, 31*(6), 757–786.

Ayas, A., Özmen, H., & Çalık, M. (2010). Students' conceptions of the particulate nature of matter at secondary and tertiary level. *International Journal of Science and Mathematics Education, 8*, 165–184.

Bogdan, R. C., & Biklen, S. K. (1998). *Qualitative research for education: An introduction to theory and methods* (3rd ed.). Boston: Allyn & Bacon.

Boz, Y. (2006). Turkish pupils' conceptions of the particulate nature of matter. *Journal of Science Education and Technology, 15*(2), 203–213.

Chandrasegaran, A. L., Treagust, D. F., & Mocerino, M. (2008). An evaluation of a teaching intervention to promote students' ability to use multiple levels of representation when describing and explaining chemical reactions. *Research in Science Education, 38*(2), 237–248. doi:10.1007/s11165-007-9046-9.

Chiu, M.-H. (2007). A national survey of students' conceptions of chemistry in Taiwan. *International Journal of Science Education, 29*(4), 421–452. doi:10.1080/09500690601072964.

de Vos, W., & Verdonk, A. H. (1996). The particulate nature of matter in science education and in science. *Journal of Research in Science Teaching, 33*(6), 657–664.

Devetak, I., Vogrinc, J., & Glazar, S. A. (2009). Assessing 16-year-old students' understanding of aqueous solution at submicroscopic level. *Research in Science Education, 39*, 157–179.

Driscoll, M. P. (2000). *Psychology of learning for instruction* (2nd ed.). Boston: Allyn & Bacon.

Fraenkel, J. R., & Wallen, N. E. (2003). *How to design and evaluate research in education* (5th ed.). New York: McGraw-Hill.

Gabel, D. L. (1993). Use of the particle nature of matter in developing conceptual understanding. *Journal of Chemical Education, 70*(3), 193–194.

Gabel, D. L., Samuel, K. V., & Hunn, D. (1987). Understanding the particulate nature of matter. *Journal of Chemical Education, 64*(8), 695–697.

García-Franco, A., & Taber, K. S. (2009). Secondary students' thinking about familiar phenomena: learners' explanations from a curriculum context where 'particles' is a key idea for organising teaching and learning. *International Journal of Science Education, 31*(14), 1917–1952.

Gomez, E. J., Benarroch, A., & Marin, N. (2006). Evaluation of the degree of coherence found in students' conceptions concerning the particulate nature of matter. *Journal of Research in Science Teaching, 43*(6), 577–598.

Griffiths, A. K., & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*(6), 611–628.

Guba, L., & Lincoln, Y. (1989). *Fourth generation evaluation*. Newbury Park: Sage Publications, Inc.

Kahveci, A. (2009). Exploring chemistry teacher candidates' profile characteristics, teaching attitudes and beliefs, and chemistry conceptions. *Chemistry Education Research and Practice, 10*, 109–120.

Kahveci, A., & Özalp, D. (2009, April). *Ontology-informed diagnostic assessment of middle and secondary students' understanding of the particulate nature of matter*. Paper presented at the National Association for Research in Science Teaching (NARST) conference, Garden Grove.

Kokkotas, P., Vlachos, I., & Koulaidis, V. (1998). Teaching the topic of the particulate nature of matter in prospective teachers' training courses. *International Journal of Science Education, 20*(3), 291–303.

Lee, O., Eichinger, D. C., Anderson, C. W., Berkheimer, G. D., & Blakeslee, T. D. (1993). Changing middle school students' conceptions of matter and molecules. *Journal of Research in Science Teaching, 30*(3), 249–270.

Liang, J.-C., Chou, C.-C., & Chiu, M.-H. (2011). Student test performances on behavior of gas particles and mismatch of teacher predictions. *Chemistry Education Research and Practice, 12*(2), 238–250. doi:10.1039/c1rp90029c.

Margel, H., Eylon, B., & Scherz, Z. (2008). A longitudinal study of junior high school students' conceptions of the structure of materials. *Journal of Research in Science Teaching, 45*(1), 132–152.

Maykut, P., & Morehouse, R. (1994). *Beginning qualitative research: A philosophic and practical guide*. London: The Falmer Press.

Nakhleh, M. B., & Samarapungavan, A. (1999). Elementary school children's beliefs about matter. *Journal of Research in Science Teaching, 36*(7), 777–805.

Nakhleh, M. B., Samarapungavan, A., & Sağlam, Y. (2005). Middle school students' beliefs about matter. *Journal of Research in Science Teaching, 42*(5), 581–612.

Nicoll, G. (2003). A qualitative investigation of undergraduate chemistry students' macroscopic interpretations of the submicroscopic structure of molecules. *Journal of Chemical Education, 80*(2), 205–213.

Novick, S., & Nussbaum, J. (1978). Junior high school pupils' understanding of the particulate nature of matter: An interview study. *Science Education, 62*(3), 273–281.

Novick, S., & Nussbaum, J. (1981). Pupils' understanding of the particulate nature of matter: A cross-age study. *Science Education, 65*(2), 187–196.

Nyachwaya, J. M., Mohamed, A.-R., Roehrig, G. H., Wood, N. B., Kern, A. L., & Schneider, J. L. (2011). The development of an open-ended drawing tool: An alternative diagnostic tool for assessing students' understanding of the particulate nature of matter. *Chemistry Education Research and Practice, 12*(2), 121–132. doi:10.1039/c1rp90017j.

Odom, A. L., & Barrow, L. H. (1995). Development and application of a 2-tier diagnostic test measuring college biology students' understanding of diffusion and osmosis after a course of instruction. *Journal of Research in Science Teaching, 32*(1), 45–61.

Othman, J., Treagust, D., & Chandrasegaran, A. L. (2008). An investigation into the relationship between students' conceptions of the particulate nature of matter and their understanding of chemical bonding. *International Journal of Science Education, 30*(11), 1531–1550.

Özalp, D., & Kahveci, A. (2009, April). *Development and pilot testing of ontology-informed distractor-driven diagnostic instrument on the particulate nature of matter*. Paper presented at the National Association for Research in Science Teaching (NARST) conference, Garden Grove.

Özmen, H. (2008). Determination of students' alternative conceptions about chemical equilibrium: A review of research and the case of Turkey. *Chemistry Education Research and Practice, 9*, 225–233.

Pınarbaşı, T., & Canpolat, N. (2003). Students' understanding of solution chemistry concepts. *Journal of Chemical Education, 80*(11), 1328–1332.

Stains, M. (2007). *Classification of chemical substances, reactions, and interactions: The effect of expertise.* Doctor of Philosophy dissertation, The University of Arizona, Tucson.

Taber, K. S. (2002). *Chemical misconceptions – Prevention, diagnosis and cure* (Classroom resources, Vol. II). London: Royal Society of Chemistry.

Taber, K. S., & García-Franco, A. (2010). Learning processes in chemistry: Drawing upon cognitive resources to learn about the particulate structure of matter. *The Journal of the Learning Sciences, 19*, 99–142.

Tan, K. C. D., Goh, N. K., Chia, L. S., & Treagust, D. F. (2002). Development and application of a two-tier multiple choice diagnostic instrument to assess high school students' understanding of inorganic chemistry qualitative analysis. *Journal of Research in Science Teaching, 39*(4), 283–301.

Tan, K. C. D., Taber, K. S., Liu, X., Coll, R. K., Lorenzo, M., Li, J., et al. (2008). Students' conceptions of ionisation energy: A cross-cultural study. *International Journal of Science Education, 30*(2), 263–283.

Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education, 10*(2), 159–169.

Treagust, D. F., Chandrasegaran, A. L., Crowley, J., Yung, B. H. W., Cheong, I. P. A., & Othman, J. (2010). Evaluating students' understanding of kinetic particle theory concepts relating to the states of matter, changes of state and diffusion: A cross-national study. *International Journal of Science and Mathematics Education, 8*, 141–164.

Treagust, D. F., Chandrasegaran, A. L., Zain, A. N. M., Ong, E. T., Karpudewan, M., & Halim, L. (2011). Evaluation of an intervention instructional program to facilitate understanding of basic particle concepts among students enrolled in several levels of study. *Chemistry Education Research and Practice, 12*(2), 15–28.

Voska, K. W., & Heikkinen, H. W. (2000). Identification and analysis of student conceptions used to solve chemical equilibrium problems. *Journal of Research in Science Teaching, 37*(2), 160–176.

White, R., & Gunstone, R. (1992). *Probing understanding*. Bristol: The Falmer Press.

Yezierski, E. J., & Birk, J. P. (2006a). Misconceptions about the particulate nature of matter. *Journal of Chemical Education, 83*(6), 954–960.

Yezierski, E. J., & Birk, J. P. (2006b). Particulate nature of matter assessment (ParNoMA) [Supplemental material]. *Journal of Chemical Education, 83*(6).

Part III
Educational Technology

Dynamic Visualizations: Tools for Understanding the Particulate Nature of Matter

Sevil Akaygun and Loretta L. Jones

Dynamic Computer Visualizations for Understanding Submicroscopic Chemistry

Visualizations are important in chemistry research because they can help convey complex, subtle molecular interactions and dynamics that are difficult to describe in words (Shepard and Cooper 1982). These types of visualizations and modeling tools are now available for use in the classroom, and they have the potential to make a profound difference in how molecular-level concepts are learned and understood (Jones et al. 2005). However, in order for molecular visualizations to play an important role in the chemistry classroom, they must be designed to promote learning. Visualizations of chemical phenomena, especially at the molecular level, can be complex, and a variety of skills may be required to represent them in an accurate and pedagogically sound manner (Kozma and Russell 1997; Zare 2002).

Not only are some visualizations difficult for learners to interpret, the learners must also connect what they are seeing to the macroscopic properties of matter. Johnstone (1993) pointed out that difficulties in learning chemistry are compounded by the relationships between the three levels of chemistry understanding: the macroscopic level of the observable and visible; the submicroscopic level of the molecular, atomic, and kinetic; and the symbolic level of symbols, equations, and mathematics. He proposed that for students to understand chemistry well, they need to

S. Akaygun (✉)
Department of Secondary School Science and Mathematics Education,
Boğaziçi University, Istanbul, Turkey
e-mail: sevil.akaygun@boun.edu.tr

L.L. Jones
Department of Chemistry and Biochemistry, University of Northern Colorado,
Greeley, CO, USA

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_13,

understand the phenomena at all three levels and to be able to make connections among them. Professional chemists are experts who work well with all three levels and easily switch one to the other. However, some researchers have found that it cannot be assumed that students understand the relationship of these levels to the submicroscopic level, as chemists do (Nakhleh 1993; Nurrenbern and Pickering 1987; Sawrey 1990).

Williamson (2008) summarized some of the research on learner understanding of the particulate state of matter. She concluded that a student's understanding of the particulate state of matter is related to the student's mental models. The studies she reviewed suggested that those models can be developed by exposure to physical models, computer-based molecular modeling programs, animations, or drawings. In a subsequent review (2011), Williamson discussed evidence for the effectiveness of visualizations and how classrooms can be structured to benefit from them. In Kozma's review of learning with media (1991), he found that the ability of media to present verbal and visual information simultaneously is an important factor in helping learners to build useful mental models, suggesting that visualizations of the particulate level of matter can be powerful learning tools.

Animations and simulations of submicroscopic and macroscopic chemistry processes have been developed and used to improve the learning of molecular structure and dynamics (Ardac and Akaygun 2004; Burke et al. 1998; Ebenezer 2001; Sanger and Greenbowe 1997a, b; Sanger et al. 2000; Williamson and Abraham 1995). Burke et al. (1998) define computer animations as a series of visual images shown rapidly on a computer screen providing the illusion of motion. According to Oakes and Rengarajan (2002), an animation is a multimedia presentation that is rich in graphics and sound, but not in interactivity. These investigators define simulations as the interactive representations that display a specific environment that enables learners to experience and understand that environment through their interactions and explorations with it. The authors argue that, in simulations, it is not always possible to re-create a real-world environment with 100 % accuracy: however, the accuracy of the representation reflects the sophistication of the simulation.

Although simulations and animations are different in terms of the level of interactivity, they both have been used as good tools for chemistry instruction. A number of studies have found that students who received instruction that included computer animations of chemical processes at the molecular level were better able to comprehend chemistry concepts involving the particulate level of matter than those who did not (Ardac and Akaygun 2004; Burke et al. 1998; Sanger and Greenbowe 1997a, b; Sanger et al. 2000; Williamson and Abraham 1995).

This chapter reviews some of the research studies that have attempted to identify the effects of computer-generated dynamic visualizations on learning and discusses their implications both for developers and for instructors. First, research on animations and still images is reviewed, followed by research on simulations and on combinations of dynamic visualizations with macroscopic observations. Finally, design principles for the development of effective visualizations are discussed.

Research on Learning from Dynamic Computer Visualizations of the Submicroscopic Level

Still Visualizations and Models

Models and images on paper or chalkboard are commonly used in the teaching of chemistry, and research verifies that even simple visual displays of molecular structure and interactions have value. For example, Alesandrini and Rigney (1981) found that 96 undergraduates completing a computer-based lesson on electrochemistry performed better on a posttest if they had a pictorial review of the concepts rather than a text review.

Dori and Barak (2001) devised an instructional module for organic chemistry that included both physical models and computer models. The 276 secondary school students in their study were divided into two groups, one of which was taught by traditional means, with molecular structures on paper or drawn by the instructor on a chalkboard. The second group worked with physical models and computer-generated three-dimensional models in an inquiry-based lesson. The students who had worked with the models showed a better understanding of concepts such as isomerism and functional group. They were also better able to make connections between the submicroscopic level and the other levels of chemistry. The investigators recommended that both physical models and virtual computer-generated models be used in the teaching of chemistry.

Wu et al. (2001) investigated how students developed understanding of chemical representations as they worked with a visualization tool, eChem, that enabled them to create and translate representations of chemical phenomena. Seventy-one 11th graders worked with eChem for 6 weeks. The results of the study showed that students improved their conceptual understanding substantially. The authors suggested that students' discussions and social interactions involved both visual and conceptual aspects that deepened their understanding

Sumfleth and Telgenbüscher (2001) studied how 21 organic chemistry students developed mental models of chemical reactions. The students were divided into three groups, matched for ability; all three groups received written text instruction. One group also studied symbolic representations of the reactions (balanced equations). The second group was given illustrations of space-filled models as well as the symbolic representations. The third group had access to three types of physical models and illustrations of seven different representations, in addition to the symbolic representations. The third group was also asked to design a lesson using these materials. The results showed that the students in the first two groups tended to memorize the symbols without a real understanding of what they meant, while students in the third group were more likely to invoke the submicroscopic level in their explanations. In this study, the use of illustrations of molecular models was not as powerful as a learning environment in which students were challenged to design instruction using hands-on models and several different representational modes.

Venkataraman (2009) found that introducing 23 undergraduates to powerful molecular modeling software enhanced their mental models of molecular structure as measured by a course examination and reflective summaries. Nicoll (2003) conducted a qualitative study of 56 undergraduates in which the students were asked to use modeling clay to represent molecular structures. The students built models that were more creative and individualistic than would have been possible with commercial modeling kits. Nicoll also observed that even advanced students did not have a good idea of how atoms were connected in a molecule when they began working with the models.

Ferk et al. (2003) studied how 124 students at different levels of education (primary, secondary, and university) interpret different kinds of molecular representations. The students were given a Chemistry Visualization Test in which they had to answer questions using a variety of representations: physical models, photographs of physical models, computer-generated models, schematic drawings in color, black-and-white schematic drawings, and stereochemical formulas. Performance on the test items was greatest when the item used one of the more concrete representations (physical model, photograph of a physical model, or a computer-generated model). Kuo et al. (2004) found a similar relationship between the abstractness of a representation and performance on a test of stereochemistry. In this study 102 organic chemistry students solved stereochemistry problems using representations of increasing abstraction: physical models, computer-generated rotatable models, three-dimensional (dashed-wedge) paper structures, or two-dimensional (Fischer or Haworth) projections. Scores on the test items were lower for the more abstract representations and highest for the physical models.

The results of these studies suggest that incorporating visualizations of the particulate level of matter can enhance student learning of chemistry, especially when combined with activities in which the students design their own representations. Those visualizations are more easily interpreted by learners when physical models or computer models are used.

Computer Animations for Understanding the Particulate Nature of Matter

Many chemical phenomena can be explained by considering the collective behavior of the particles. The collective behavior of particles is difficult to understand but can be represented by dynamic computer visualizations such as animations. Research on the effects of computer animations has shown that animations of the particulate level of matter can help students to better visualize the particulate nature of matter (Rieber 1990), enhance conceptual understanding (Ardac and Akaygun 2004; Ebenezer 2001; Williamson and Abraham 1995), and help them overcome their misconceptions (Burke et al. 1998; Sanger and Greenbowe 1997b).

In a study of 52 eighth-grade students, Ardac and Akaygun (2005) examined the effectiveness of visually enhanced instruction intended to improve molecular understanding of chemical change. Instruction was designed in two different visual elaboration levels: static images presented to a whole class and computer animations presented on an individual basis or to the whole class. The results of the study indicated that students who used dynamic visuals achieved significantly higher scores on a test compared with those who used static visuals. The authors also reported that students who used dynamic visuals on an individual basis were more consistent in their use of molecular representations compared with students who received whole-class instruction with dynamic or static visuals.

Williamson and Abraham (1995) investigated the effect of visual displays on improving college-level general chemistry students' understanding of the particulate nature of matter. They used computer animations depicting the particulate nature and behavior of matter in two ways: as a supplement in large lectures and as individual activity as well as lecture supplement. They compared the mental models of students in both groups with those of students in a control group that did not view the animations. Their results showed the relative superiority of dynamic visuals over static visuals, as students who received instruction including dynamic visualizations achieved significantly higher conceptual understanding than did the control group. The dynamic quality of the computer animations may have enabled more expert-like mental models of the particulate nature of matter, when compared with static visuals such as transparencies or chalk diagrams.

Animations accompanied by instruction have helped students confront their misconceptions and increase the accuracy of their understandings. Sanger and Greenbowe (1997a, b) used an animation of electrons flowing in electrolyte solutions and salt bridges as part of an instructional unit on electrochemical cells. They found that the animations helped students to visualize chemical reactions occurring inside electrochemical cells at the submicroscopic level and decreased the proportion of students exhibiting misconceptions.

Tasker (1998) indicated that animations of submicroscopic world require imagination and can help learners generate accurate mental models of invisible phenomena. When he showed an animation of the submicroscopic nature of boiling water to university students, the majority of them corrected their misconception that "the bubbles of water contain air" after viewing the animation only once.

Many dynamic visualizations have been designed to include both macroscopic and submicroscopic representations to teach the fundamental concepts of chemistry. Ardac and Akaygun (2004) investigated the combined effects of multimedia instruction that presented the macroscopic, symbolic, and molecular levels of phenomena on the test performance of 49 eighth-grade students. They found that students who had been exposed to multimedia instruction performed significantly better on items related to the molecular state of chemical phenomena than students who had not received multimedia instruction.

Tasker and Dalton (2006) investigated factors that affect students' abilities to form scientifically accurate mental models of chemistry concepts at the molecular level after viewing a series of molecular-level animations. They used a pretest/posttest design with follow-up interviews to examine the changes in the mental models of 48 first-year general chemistry students following a semester of teaching in which molecular animations had been used on a regular basis. The results of their study showed that the number of scientifically acceptable “key features” in students’ representations significantly increased, suggesting that the students developed more vivid mental imagery of particulate phenomena. In the interviews students frequently referred to the animations in their explanations.

Gregorius et al. (2010a) developed and used a dynamic animation module to teach the states of matter to elementary students and solution chemistry to secondary students. They then compared the effects of the intervention with traditional teaching methods. The results showed that students in each grade level who received animations outperformed the students in the traditional classes. In the second part of the study, Gregorius et al. (2010b) divided the 72 participants into two groups according to whether they were judged to have low base knowledge or high base knowledge. The authors stated that the students with low base knowledge performed at the level of students with high base knowledge after viewing the animation module. They suggested that animations may provide differentiated learning for low base knowledge students.

The effectiveness of different styles of animations of the particulate level of matter has been compared by some researchers. Kelly and Jones (2007) investigated how the features of two different styles of submicroscopic level animations of the dissolving of sodium chloride in water affected the conceptual explanations of 18 college-level general chemistry students. In their qualitative study, the authors found that students could incorporate some of the submicroscopic structural and functional features from the animations without a cohesive understanding. In general, students’ drawings improved after viewing the animations, but some students retained prior misconceptions in their drawing and explanations. Kelly and Jones (2008) also investigated whether these students were able to transfer their understanding to a novel situation. Their results suggested that although students incorporated some features of animations into their explanations, they had difficulty in transferring these ideas to new situations. The authors argued that students need to have scientific terms reinforced and help in connecting new concepts to old ones.

Not all studies have shown a positive learning effect from animations. In a study of how students learn about electrochemical cells, Sanger and Greenbowe (2000) gave 135 undergraduates a presentation of a conceptual change unit that included demonstrations. In addition, one group of students received a lecture, and the other group viewed computer-based animations of an electrochemical cell that were narrated by an instructor. The animations were repeated for a total of three viewings. The results of this study showed that the conceptual change unit was the most powerful learning tool. The animations did not appear to add greater understanding when compared to the lecture presentation and may have distracted students from some of the target concepts.

Vermaat et al. (2003) investigated the ability of students to make connections between the macroscopic, symbolic, and molecular levels of chemistry. In the study, students were interviewed before and after being exposed to instruction that included molecular-level animations and information about applications of the reactions. When the unit was completed, students were interviewed and made concept maps linking the various levels of chemistry. However, most of the links were drawn between the real-world applications and the macroscopic and symbolic levels of chemistry. Although the students mentioned that they enjoyed the animations in the interviews, few of them included the particulate level in their concept maps and did not think to mention them during the interviews.

Animations have been incorporated into hypermedia environments that combine multimedia and hypertext in order to enhance conceptual understanding at the submicroscopic level. Ebenezer (2001) used hypermedia environments to explore 11th-grade students' conceptions of the dissolving of sodium chloride in water. The analysis of students' expressions and representations indicated that the animations helped students to visualize solution chemistry, specifically how melting was different than dissolving, how ions formed, and how hydration took place.

Animations and Individual Differences

Some research has incorporated individual differences into studies of the effect of animations. The interaction of spatial ability with animations was investigated by Yang et al. (2003). In this study 415 undergraduates were categorized as either high spatial ability or low spatial ability. All students received a lecture on the operation of batteries, but those in one lecture section then watched animations of the process that focused on the submicroscopic level while the instructor narrated, while students in the other lecture section watched still images of screens from the animation along with instructor discussion. Students who had viewed the animations scored higher on a test of conceptual understanding than students who had viewed still images, and no interaction with spatial ability was detected. However, in a test of the ability of the students to transfer their knowledge, viewing the animation led to higher average scores only for students in the high spatial ability group. This finding suggests that students with low spatial ability may have more difficulty transferring knowledge gained from viewing animations.

The effect of gender on the ability of students to learn from submicroscopic level animations has also been investigated. Yezierski and Birk (2006) used submicroscopic animations of the particulate nature of matter to close the gender gap. In their study, authors developed and used an instrument to assess understanding of the particulate nature of matter before and after viewing the animations. The results showed that the animations helped both male and female students to improve their scores, but that the gain in score for female students was significantly greater than that for male students. Although the scores of the female students on the pretest were lower than those of the male students, there was no gender difference in post-test scores.

Falvo and Suits (2009) found that female undergraduates outperformed male undergraduates after viewing an animation of the dissolution of sodium chloride. The authors suspected that the male students may have been processing the visual information differently from the female students. Other individual differences may also be important in learning from animations. For example, Suits and Diack (2002) proposed that students with different cognitive styles may respond differently to the same animation. Some students may focus more on narration or text, while others may be more observant of the visual phenomenon but perceive it in different ways.

Computer Simulations for Understanding the Particulate Nature of Matter

Computer simulations have been used in a variety of chemistry courses and laboratory applications for different levels of students. Early applications of simulations were directed toward general chemistry laboratories and most simulated macroscopic laboratory procedures (Barker and Fredericks 1977; Butler and Griffin 1979; Moore et al. 1980; Dwight 1981; Whisnant 1984; Smith et al. 1986; Jones 1988). Later simulations focused on the teaching of many chemistry concepts, such as chemical kinetics (Steffen and Holt 1993), atomic structure and periodic properties (Martin 2002), chemical reactions (Xie and Tinker 2006), solubility equilibrium (Gil and Paiva 2006), and general chemistry topics (Jones and Tasker 2002).

Jong and Joolingen (1998) reviewed research papers that addressed the effectiveness of simulations in promoting scientific discovery learning and the problems that learners may have as they use discovery learning. Many of the research studies that identify problems with a simulation also report ways to provide support for learners so that they can make effective use of the simulation (Jong and Joolingen 1998). Robinson (2000) added that three methods of support seem to influence learning outcomes from simulations in a positive way:

1. Providing direct access to information about the domain of the simulation and presenting information concurrently with the simulation so that it is available at the appropriate time.
2. Providing learners with assignments, questions, exercises, or games, because they provide the learner with a goal.
3. Introducing the components of the simulation to the learners gradually rather than introducing the full complexity of the simulation at once.

Jones and Tasker (2002) developed the interactive computer program, *Bridging to the Lab: Media Connecting Chemistry Concepts with Practice*, each module of which is set in the context of a real-life problem. Students who use the module make decisions regarding experimental design, observe simulations of reactions and other laboratory processes (at both macroscopic and molecular levels), record and interpret data, perform calculations, and draw conclusions from their results. Feedback is provided to assist students when they make mistakes. Yeung et al.

(2008) reported that students who used *Bridging to the Lab* modules performed significantly better on a posttest than students who had not.

Stieff and Wilensky (2003) investigated the effects of a modeling and simulation package, *Connected Chemistry*, on students' understanding of "how macro-level patterns in chemistry result from the interactions of many molecules on a submicro level." Six undergraduate science majors interacted with *Connected Chemistry* and participated in 90-min interviews after using it. The results of the study suggested that prior to *Connected Chemistry*, students' explanations of chemical equilibrium included memorized facts, whereas after interacting with the simulation, they showed better conceptual understanding of the nature of chemical equilibrium and logical reasoning.

Gil and Paiva (2006) used a simulation of the solubility equilibrium of four different salts to facilitate the thermodynamic interpretation of solubility differences. The authors pointed out that the computer simulation provided qualitative depictions of the "before" and the "after" states when equal amounts of two salts, such as NaCl and $CaCO_3$, are added to identical volumes of water. Gil and Paiva (2006) found that the simulation facilitated the instructor's qualitative introduction to the concepts.

Winberg and Berg (2007) investigated the effects of acid–base titration simulations prior to a university-level chemistry laboratory activity. The types of questions students asked of their instructors were used as indicators of their cognitive focus. The authors suggested that the simulation influenced students toward posing more theoretical questions during their laboratory application, and their interviews showed that the students exhibited a more complex, correct use of chemistry knowledge regardless of their attitudes.

Abdullah and Shariff (2008) investigated the effects of an inquiry-based computer simulation used with two types of cooperative learning environments on scientific reasoning and conceptual understanding of the particulate behavior of gases. Three hundred and one secondary school students were randomly assigned either to one of the two treatment groups or to a control group. All three groups completed the *Gas Law Simulation* lessons accompanied by a worksheet in four 70–80-min sessions, but students in the heterogeneous-ability cooperative learning group were assigned to groups composed of students of different ability and students in the friendship cooperative learning group were allowed to form groups with their friends. Students in the control group worked individually. Students who worked with the simulation in the heterogeneous-ability cooperative learning environment outperformed their counterparts in the friendship cooperative learning environment, and the ones in the friendship cooperative learning environment outperformed their counterparts in the control group on enhanced scientific reasoning and conceptual understanding of the particulate nature of gases and gas laws. These findings suggest that having the opportunity to explain content to another student can be important in learning from simulations.

Worksheets are commonly used to provide support for students viewing animations and simulations. Akaygun and Jones (2013a) investigated the effect of the level of guidance provided by worksheets on the conceptual understanding of students who viewed particulate-level simulations of physical equilibrium (liquid-vapor and solubility). In this study, 191 college-level general chemistry students

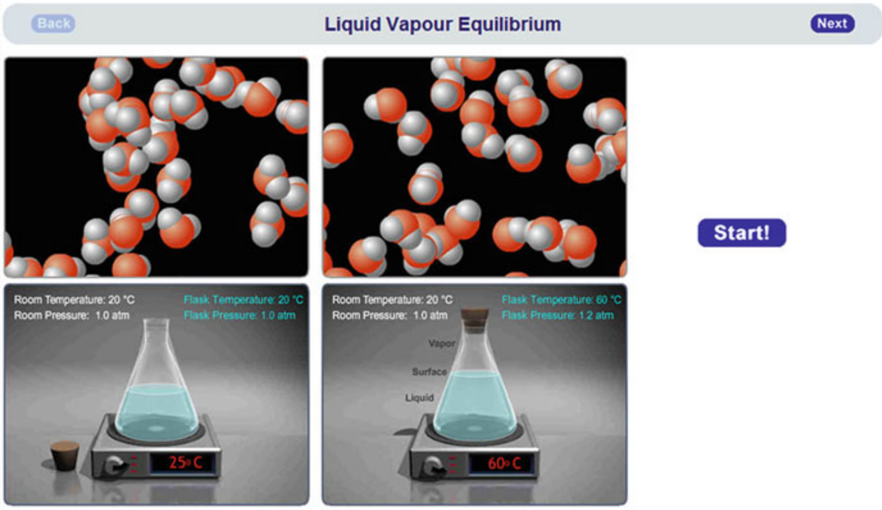


Fig. 1 A screen from a liquid–vapor equilibrium simulation, developed by Akaygun and Jones (2007) (The simulation is available at: http://artsci.drake.edu/honts/molviz/page2/page2.html)

worked with a simulation of liquid–vapor equilibrium, developed by Akaygun and Jones (2013b), for about 2 h and completed an open-ended conceptual questionnaire before and after working with the simulation. The simulation included macroscopic and submicroscopic representations depicting the situation before and at the condition of equilibrium. After completing the simulation, the students were found to have significantly better conceptual understanding of equilibrium and their mental models had improved, regardless of the level of guidance provided (Fig. 1).

Akaygun (2009) investigated the effects of a submicroscopic level simulation of solubility equilibrium, shown in Fig. 2, on students' understandings of solubility equilibrium. In this study, novice chemistry students were asked to use the simulation to prepare saturated solutions of different salts and to describe the processes in the solution, for about 2 h. Students completed pre- and posttests on the dynamic nature of equilibrium, and post interviews were conducted. The results of the study showed that students improved their understanding of the dynamic nature of solubility equilibrium.

Combining Animations and Demonstrations or Laboratory Work

For better understanding of chemistry, dynamic visualizations of macroscopic and submicroscopic levels have been combined and their effects investigated. Velázquez-Marcano et al. (2004) investigated whether a video demonstration or a submicroscopic animation better enhanced students' conceptual understanding of

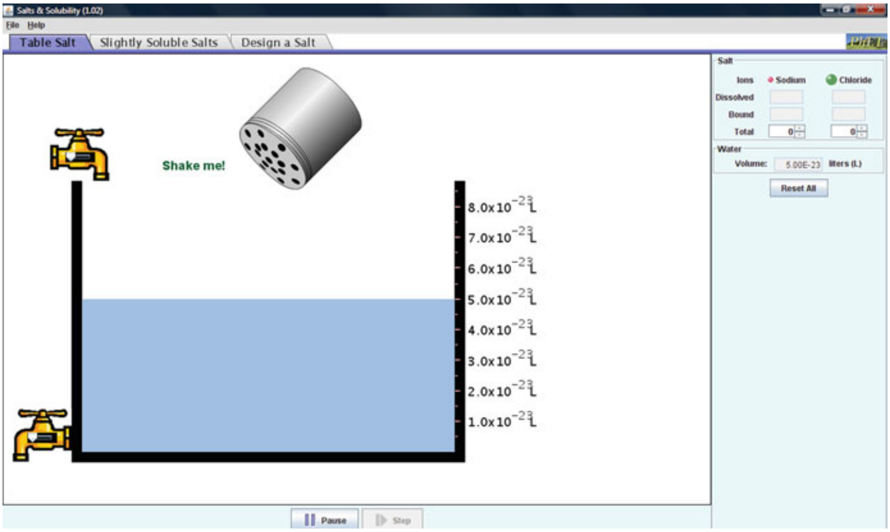


Fig. 2 A screen from the solubility equilibrium simulation (The simulation is available at: http://phet.colorado.edu/en/simulation/soluble-salts) (Image courtesy of PhET Interactive Simulations research group at the University of Colorado Boulder)

gas behavior by showing them individually as well as one visualization after the other in both orders. The authors indicated that neither the video demonstration nor the submicroscopic animation was sufficient to obtain the maximum student performance by itself. The combined use of video demonstration and submicroscopic animation helped students significantly more than using only one of them, because the integration of both levels enabled them to visualize the process and, hence, enhanced understanding. No effect of ordering was seen.

Abraham et al. (2001) developed a series of animations linked to specific laboratory activities. They found that students who completed both the animations and the related laboratory activities were better able to provide particulate-level explanations for their macroscopic laboratory observations than were students who completed only the laboratory activities.

Sanger et al. (2000) created a computer animation depicting the behavior of gas molecules occurring in a can-crushing demonstration, based on the misconceptions of students identified by a quiz given after the same demonstration was shown. The authors showed the animation they created to another group of students along with the demonstration and compared their understanding with a group of students who received instruction that included the can-crushing demonstration but no animation. Their results showed that the students who had viewed the animation of the particulate behavior of gases as a part of their instruction had better conceptual understanding than the ones who did not. In a follow-up study, Kelly et al. (2004) found that when secondary school students viewed an animation in conjunction with a demonstration of a can being crushed by atmospheric pressure, they had a better understanding of the molecular basis of the process.

Supasorn et al. (2008) developed two versions of a prelaboratory simulation for a laboratory activity on organic extractions. One version used text captions to describe the simulation; the other used narration. Students completing the simulation with written captions performed significantly better than those who completed the simulation with narration. The authors thought that this difference may have been due to the fact that the written captions could be read over and over again, while the narration was normally played only once.

Limitations of Animations and Simulations

As described previously, animations and simulations can be useful tools in the chemistry classroom. However, care must be taken in their selection and usage. A limitation of animations is that they are just simple representations of the submicroscopic level and cannot be perfectly accurate. Students may develop simplistic or incomplete understanding of the submicroscopic level as a result of viewing animations (Tasker 1998). Not all studies of animations and simulations have revealed positive effects.

Papageorgiou et al. (2008) investigated how sixth graders' particulate understanding of evaporation and melting was affected by particulate-level animations. The experimental group was taught using software on evaporation and melting, which included photographs of the macroscopic state and animations showing the motion of the particles; the control group was not. Both groups showed improvement in their understanding of the concepts of distribution of energy but little added benefit from the software was found. The authors argued that students could not escape from their initial views and created synthetic explanations for macroscopic and submicroscopic characteristics that matched their misconceptions.

Stieff et al. (2011) found by the use of eye-tracking technology that students do not always notice the critical aspects of a multi-representational display. Organic chemistry students in their study viewed computer simulations of molecular mechanics such as vibration and bond stretching. The simulations used simultaneous presentation of images of ball-and-stick models, mathematical equations, and a graph. Students could change the variables in the model and see the resulting changes in the molecular energy in the equation and graph. Analysis of the data showed that students attended equally to the models and graphs but tended to ignore the equations.

Learners can also develop misconceptions about the particulate state of matter because of the limitations of the technology. Chandrasegaran et al. (2008) found that learners often retain prior misconceptions despite viewing accurate structures and processes in an animation. Kelly and Jones (2007) found that students may develop new misconceptions upon viewing an animation. For example, some students misinterpreted an animation of the hydration of ions to mean that a chemical reaction had occurred. It was also discovered in this study that different students viewing the same animation saw different things and that some students did not notice phenomena that conflicted with their preconceptions. For example, a student viewing an animation of a sodium chloride crystal did not notice that the ions were vibrating until another student pointed it out. These findings suggest that it would be useful for instructors to provide direction to students before they view an animation and to allow time for discussion afterward.

Tversky et al. (2002) reviewed a number of studies on animations of scientific concepts. They compared the effects of animations with static diagrams of the same concepts on students' understanding. The authors argued that the animations could convey more information about the micro-steps but had no benefits over the still images. Tversky et al. (2002) believed that the lack of benefit from the animations might have been related to the fact that animations are difficult to perceive because of the cognitive limitations in processing a dynamic visual. Successful animations were found to have two major characteristics: first, the animation must be easy to perceive and comprehend, and, second, the conceptual change to be conveyed must be apparent from the animation (Tversky et al. 2002).

Some research indicates that providing learners with dynamic information in an explicit form does not necessarily result in better learning. Lowe (2003) indicated that animations can confront learners with additional and qualitatively different information-processing demands from those they face with static visuals. Specifically, students with lower academic backgrounds may find it difficult to extract information from complex animations. Lewalter (2003) commented on the transitory nature of animations when discussing the results of a study that found no performance differences between students who used static or dynamic visuals. She claimed that although dynamic visuals may reduce the load of cognitive processing through supporting the construction of a mental model, their transitory nature may cause higher cognitive load since learners may have less control of their cognitive processing. According to Lowe (2003), although animations can provide learners with explicit dynamic information that is unavailable in static images, the temporarily changing screens may introduce additional information-processing demands. Similarly, Rieber (1991) states that dynamic displays demand higher levels of attention when compared with static displays.

Cognitive theories of multimedia learning suggest that when students are required to pay attention to several tasks simultaneously, a portion of the working memory may not be available for learning (Mayer 1997). Having different types of representations in a visualization may cause learners to experience difficulties in processing this information. Mayer and Moreno (1998) argue that focusing on one type of presentation component may result in missing information from a different presentation component, because of the split-attention effect. Lowe (2003) suggests that the split-attention effect is observed when learners have to attend to multiple presentation sources (like picture-text combinations) and may also occur when learners are attending to a single presentation that includes temporal changes (like an animation or a simulation). Allowing learners to control the variables in a dynamic visual can reduce the effect of split attention.

Effective Design of Visualizations

Research shows that the effectiveness of animations can be increased by using attention-gaining tools such as adjunct questions (Holliday and McGuire 1992; Lekhavat and Jones 2009), additional practice (Rieber 1990), or explicit reasoning (Kozma and Russell 1997). Students may initially require support in learning to interpret molecular representations (Kozma 2000; Sanger 2000).

For clarity and simplicity, simulations can represent reality in a simplified format. Gil and Paiva (2006) claim that when using graphical simulations, students should be informed that only a small number of particles is represented, the large spaces shown between particles in a liquid are not realistic, and illustrations of only some molecular motions are shown, in order to emphasize particular aspects.

Jones et al. (2008) developed a set of design principles for effective molecular visualizations. They suggest that an effective animation should optimize narration, graphics, and color for efficient sensory perception, that an introduction or orientation should be provided to help learners make connections to prior knowledge, that aids to direct attention be provided, and that the rate of information delivery be limited so as not to exceed the working memory of the viewer.

Implications for Educators

Visualizations of the particulate level of matter that have been used in chemistry instruction may help novice learners to enhance their mental models and to reach a better conceptual understanding if they are used effectively. To promote learning from visualizations, instructors of chemistry may need to include supplementary materials such as worksheets, handouts, or adjunct questions that will guide students and help them to build scientifically accurate mental models.

Dynamic visualizations of the particulate level of matter have been shown to help students build productive mental models of submicroscopic phenomena and to make connections between the macroscopic, symbolic, and submicroscopic levels of chemistry. Therefore, dynamic visualizations can be linked to laboratory instruction so that the students can explain the changes they observe during their laboratory work in terms of processes occurring at the submicroscopic level.

Visualizations used in teaching and learning may not always lead to accurate changes in mental models. Students may misunderstand or gain misconceptions about chemistry concepts. Instructors may need to check on student understanding during lessons. One way to do this is by using supportive worksheets along with the visualization and asking follow-up questions. Class discussion, having students think aloud, and peer collaboration can be incorporated into the lesson to enhance learning from visualizations.

Summary

Visualizations have been used by chemistry instructors to help students understand phenomena at the particulate level and connect them to the macroscopic level. Students' understandings of chemical phenomena are related to the mental models they possess (Williamson 2008) and can be developed as the students interact with different environments such as physical models, static pictures, computer-based models, animations, and simulations.

Understanding chemical phenomena involves understanding the structure and behavior of particles, which are not observable. Consequently, models have been used to help instructors and learners to communicate representations. Visualizations created by computers are being used in chemistry instruction. Computer models are used to depict the structure of organic molecules (Dori and Barak 2001), to teach electrochemistry (Sanger and Greenbowe 2000), to conduct molecular modeling (Venkataraman 2009), and to distinguish pure substances and mixtures (Sanger 2000).

Most chemical phenomena involve dynamic processes occurring at the submicroscopic level, which cannot be shown in any environment but can be represented by various tools or models. Dynamic visualizations are tools that allow learners to visualize and conceptualize the motion or dynamic processes of particles. Animations and simulations are two types of dynamic visualizations that provide learners either with a multimedia presentation rich in sound and graphics (the former) or an interactive environment in which learners are allowed to make changes in the variables (the latter). Both animations and simulations have been developed and used to improve the learning of molecular structure and dynamics (Burke et al. 1998; Jones and Tasker 2002; Sanger and Greenbowe 1997b; Sanger et al. 2000; Williamson and Abraham 1995; Xie and Tinker 2006).

Many studies have investigated the effects of computer animations of the particulate level of matter and found that they can help students better to visualize the particulate nature of matter (Rieber 1990), enhance conceptual understanding (Ebenezer 2001; Williamson and Abraham 1995; Yezierski and Birk 2006), and help learners overcome their misconceptions (Burke et al. 1998; Sanger and Greenbowe 1997b).

The effects of dynamic simulations have also been investigated, and it has been found that they may lead to enhanced scientific discovery learning (Jong and Joolingen 1998), better conceptual understanding (Akaygun 2009; Xie and Tinker 2006; Yeung et al. 2008), and better connections of the particulate and macroscopic levels (Stieff and Wilensky 2003).

Laboratory applications and macroscopic observations are important aspects of chemistry. When simulations including laboratory observations have been developed, they have been found to be effective in helping students achieve better conceptual understanding (Abraham et al. 2001; Kelly et al. 2004; Smith et al. 1986; Supasorn et al. 2008).

Despite the generally positive effects of dynamic visualizations, they also have some limitations. For example, they may cause students to develop simplistic and inaccurate mental models (Tasker 1998). Prior knowledge of students needs to be considered when animations are used in instruction (Williams 1996), and students may develop misconceptions from the visualizations (Kelly and Jones 2007; Tasker 1998). Finally, animations may increase cognitive load unless they are carefully designed and used (Mayer and Moreno 1998; Lowe 2003).

Dynamic visualizations have been investigated and found to be effective if well designed and appropriately used, and their effectiveness can be increased by using attention-gaining tools such as worksheets containing questions (Holliday and McGuire 1992; Lekhavat and Jones 2009), extra practice (Rieber 1990), or explicit reasoning (Kozma and Russell 1997). The format of the visualizations should be kept basic for clarity and simplicity. Jones et al. (2008) developed a set of design principles for effective molecular visualizations including optimization of narration, graphics, and color for efficient sensory perception and an introduction or orientation to help learners make connections to prior knowledge.

References

Abdullah, S., & Shariff, A. (2008). The effects of inquiry-based computer simulation with cooperative learning on scientific thinking and conceptual understanding of gas laws. *Eurasia Journal of Mathematics, Science, and Technology Education, 4*(4), 387–398.

Abraham, M. R., Gelder, J. L., & Haines, K. (2001). A web-based molecular-level inquiry laboratory activity. *The Chemical Educator, 6*, 307–308.

Akaygun, S. (2009). *The effect of computer visualizations on students' mental models of dynamic nature of physical equilibrium*. Doctoral dissertation, University of Northern Colorado, Greeley.

Akaygun, S., & Jones, L. L. (2013a). How does level of guidance affect understanding when students use a dynamic simulation of liquid–vapor equilibrium? In I. Devetak, S. A. Glazar, & L. Plut-Pregelj (Eds.), *Active learning and understanding in the chemistry classroom*. Dordrecht/London: Springer.

Akaygun, S., & Jones, L. L. (2013b). Research-based design and development of a simulation of liquid–vapor equilibrium. *Chemistry Education Research and Practice*. doi:10.1039/C3RP00002H.

Alesandrini, K. L., & Rigney, J. W. (1981). Pictorial presentation and review strategies in science learning. *Journal of Research in Science Teaching, 18*(3), 465–474.

Ardac, D., & Akaygun, S. (2004). Effectiveness of multimedia-based instruction that emphasizes molecular representations on students' understanding of chemical change. *Journal of Research in Science Teaching, 40*(4), 317–337.

Ardac, D., & Akaygun, S. (2005). Using static and dynamic visuals to represent chemical change at molecular level. *International Journal of Science Education, 27*(11), 1269–1298.

Barker, F., & Fredericks, R. (1977). Development of computer simulations for use in a high school chemistry course (HSF). *Journal of Chemical Education, 54*, 113.

Burke, K., Greenbowe, T., & Windschitl, M. (1998). Developing and using conceptual computer animations for chemistry instruction. *Journal of Chemical Education, 75*(12), 1658–1661.

Butler, W. M., & Griffin, H. C. (1979). Simulations in the general chemistry laboratory with microcomputers. *Journal of Chemical Education, 56*, 543.

Chandrasegaran, A. L., Treagust, D. F., & Mocerino, M. (2008). An evaluation of a teacher intervention to promote students' ability to use multiple levels of representation when describing and explaining chemical reactions. *Research in Science Education, 38*(2), 237–248.

Dori, Y. J., & Barak, M. (2001). Virtual and physical molecular modeling: Fostering model perception and spatial understanding. *Educational Technology & Society, 4*(1), 61–74.

Dwight, T. C. (1981). Laboratory simulations that include experimental error (CS). *Journal of Chemical Education, 1981*(58), 407.

Ebenezer, J. (2001). A hypermedia environment to explore and negotiate students' conceptions: Animation of the solution process of table salt. *Journal of Science Education and Technology, 10*, 73–91.

Falvo, D. A., & Suits, J. P. (2009). Gender and spatial ability and the use of specific labels and diagrammatic arrows in a micro-level chemistry animation. *Journal of Educational Computing Research, 41*(1), 83–102.

Ferk, V., Vrtacnik, M., Blejec, A., & Gril, A. (2003). Students' understanding of molecular structure representations. *International Journal of Science Education, 25*(10), 1227–1245.

Gil, V. M. S., & Paiva, J. C. M. (2006). Using computer simulations to teach salt solubility. The role of entropy in solubility equilibrium. *Journal of Chemical Education, 83*, 170.

Gregorius, R. M., Santos, R., Dano, J. B., & Gutierrez, J. J. (2010a). Can animations effectively substitute for traditional teaching methods? Part I: Preparation and testing of materials. *Chemistry Education Research and Practice, 11*, 253–261.

Gregorius, R. M., Santos, R., Dano, J. B., & Gutierrez, J. J. (2010b). Can animations effectively substitute for traditional teaching methods? Part II: Potential for differentiated learning. *Chemistry Education Research and Practice, 11*, 262–266.

Holliday, W. G., & McGuire, B. (1992). How can comprehension adjunct questions focus students' attention and enhance concept learning of a computer-animated science lesson? *Journal of Research in Science Teaching, 29*(1), 3–16.

Johnstone, A. H. (1993). The development of chemistry teaching: A changing response to changing demand. *Journal of Chemical Education, 70*(9), 701–704.

Jones, L. L. (1988). Enhancing Instruction in the practice of chemistry with the computer-assisted interactive videodisc. *Trends in Analytical Chemistry, 7*, 273–276.

Jones, L., & Tasker, R. (2002). *Bridging to the lab: Media connecting chemistry concepts with practice*. New York: W.H. Freeman and Company.

Jones, L. L., Stillings, N. A., & Jordan, K. D. (2005). Molecular visualization in chemistry education: The role of multidisciplinary collaboration. *Chemistry Education Research and Practice, 6*(3), 136–149.

Jones, L., Honts, J., Tasker, R., Tversky, B., Suits, J., Falvo, D., & Kelly, R. (2008). Designing effective visualizations of molecular structure and dynamics. Available at: http://artsci.drake.edu/honts/molviz/assets/ConfChem08-MolAni.pdf. Accessed 5 May 2011.

Jong, D. T., & Joolingen, V. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research, 68*, 179–201.

Kelly, R. M., & Jones, L. L. (2007). Exploring how different features of animations of sodium chloride dissolving affect students' explanations. *Journal of Science Education and Technology, 16*(5), 413–429.

Kelly, R. M., & Jones, L. L. (2008). Investigating students' ability to transfer ideas learned from molecular animations of the dissolution process. *Journal of Chemical Education, 85*(2), 303–309.

Kelly, R. M., Phelps, A. J., & Sanger, M. J. (2004). The effects of a computer animation on students' conceptual understanding of a can-crushing demonstration at the macroscopic, microscopic, and symbolic levels. *The Chemical Educator, 9*(3), 184–189.

Kozma, R. B. (1991). Learning with media. *Review of Educational Research, 61*(2), 179–212.

Kozma, R. B. (2000). The use of multiple representations and the social construction of understanding in chemistry. In M. J. Jacopson & R. B. Kozma (Eds.), *Innovations in science and mathematics education* (pp. 11–45). Mahwah: Lawrence Erlbaum Associates.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching, 34*(9), 949–968.

Kuo, M.-T., Jones, L. L., Pulos, S. M., & Hyslop, R. M. (2004). The role of molecular representations, complexity, and orientation in stereochemistry problem solving. *The Chemical Educator, 9*, 1–7.
Lekhavat, P., & Jones, L. (2009). The effect of adjunct questions emphasizing the particulate nature of matter on students' understanding of chemical concepts in multimedia lessons. *Educacion Quimica, 20*(3), 351–359.
Lewalter, D. (2003). Cognitive strategies for learning from static and dynamic visuals. *Learning and Instruction, 13*, 177–189.
Lowe, R. K. (2003). Animation and learning: Selective processing of information in dynamic graphics. *Learning and Instruction, 13*, 157–176.
Martin, J. S. (2002). SIRs: Simulations and interactive resources for Windows. *Journal of Chemical Education, 79*, 639.
Mayer, R. E. (1997). Multimedia learning: Are we asking the right questions? *Educational Psychologist, 32*, 1–19.
Mayer, R. E., & Moreno, R. (1998). A split-attention attention effect in multimedia learning: Evidence for dual information processing systems in working memory. *Journal of Educational Psychology, 90*, 312–320.
Moore, C., Smith, S. G., & Avner, R. A. (1980). Facilitation of laboratory performance through CAI. *Journal of Chemical Education, 57*, 196–198.
Nakhleh, M. (1993). Are our students conceptual thinkers or algorithmic problem solvers? *Journal of Chemical Education, 70*(1), 52–55.
Nicoll, G. (2003). A qualitative investigation of undergraduate chemistry students' macroscopic interpretations of the submicroscopic structure of molecules. *Journal of Chemical Education, 80*(2), 205–213.
Nurrenbern, S. C., & Pickering, M. (1987). Concept learning versus problem solving: Is there a difference? *Journal of Chemical Education, 64*(6), 508–509.
Oakes, K., & Rengarajan, R. (2002). Practice makes perfect – E-Learning – Simulation in training. http://findarticles.com/p/articles/mi_m0MNT/is_11_56/ai_94174474. Accessed 8 Oct 2008.
Papageorgiou, G., Johnson, P., & Fotiades, F. (2008). Explaining melting and evaporation below boiling point. Can software help with particle ideas? *Research in Science & Technological Education, 26*(2), 165–183.
Rieber, L. P. (1990). Using computer animated graphics in science instruction with children. *Journal of Educational Psychology, 82*(1), 135–140.
Rieber, L. P. (1991). Animation, incidental learning and continuing motivation. *Journal of Educational Psychology, 83*(3), 318–328.
Robinson, W. R. (2000). A view of the science education research literature: Scientific discovery learning with computer simulations. *Journal of Chemical Education, 77*, 17.
Sanger, M. (2000). Using particulate drawings to determine and improve students' conceptions of pure substances and mixtures. *Journal of Chemical Education, 77*(6), 762–766.
Sanger, M., & Greenbowe, T. (1997a). Common student misconceptions in electrochemistry: Galvanic, electrolytic, and concentration cells. *Journal of Research in Science Teaching, 34*(4), 377–398.
Sanger, M., & Greenbowe, T. (1997b). Students' misconceptions in electrochemistry: Current flow in electrolyte solutions and the salt bridge. *Journal of Chemical Education, 74*(7), 819–823.
Sanger, M. J., & Greenbowe, T. J. (2000). Addressing student misconceptions concerning electron flow in aqueous solutions with instruction including computer animations and conceptual change strategies. *International Journal of Science Education, 22*(5), 521–537.
Sanger, M., Phelps, A., & Fienhold, J. (2000). Using a computer animation to improve students' conceptual understanding of a can-crushing demonstration. *Journal of Chemical Education, 77*(11), 1517–1520.
Sawrey, B. (1990). Concept learning versus problem solving: Revisited. *Journal of Chemical Education, 67*(3), 253–254.
Shepard, R. N., & Cooper, L. A. (1982). *Mental images and their transformations*. Cambridge, MA: MIT Press.

Smith, S. G., Jones, L. L., & Waugh, M. L. (1986). Production and evaluation of interactive videodisc lessons in laboratory instruction. *Journal of Computer-Based Instruction, 13*, 117–124.
Steffen, L. K., & Holt, P. L. (1993). Computer simulations of chemical kinetics (CS). *Journal of Chemical Education, 70*, 991.
Stieff, M., & Wilensky, U. (2003). Connected chemistry – Incorporating interactive simulations into the chemistry classroom. *Journal of Science Education and Technology, 12*(3), 285–302.
Stieff, M., Hegarty, M., & Deslongchamps, G. (2011). Identifying representational competence with multi-representational displays. *Cognition and Instruction, 29*(1), 123–145.
Suits, J. P., & Diack, M. (2002). Instructional design of scientific simulations and modeling software to support student construction of perceptual to conceptual bridges. *Educational Multimedia, Hypermedia & Telecommunications, Proceedings, 3*, 1904–1909.
Sumfleth, E., & Telgenbüscher, L. (2001). Improving the use of instructional illustrations in learning chemistry. In H. Behrendt (Ed.), *Research in science education – Past, present, and future* (pp. 289–294). Dordrecht: Kluwer Academic Publishers.
Supasorn, S., Suits, J. P., Jones, L. L., & Vibuljun, S. (2008). Impact of a pre-laboratory computer simulation of organic extraction on comprehension and attitudes of undergraduates. *Chemical Education Research and Practice, 9*, 169–181.
Tasker, R. (1998). The VisChem project: molecular level animations in chemistry – potential and gain. *UniServe Science News, 9*. Available online at: http://science.uniserve.edu.au/newsletter/vol9/tasker.html. Accessed 10 May 2007.
Tasker, R., & Dalton, R. (2006). Research into practice: Visualisation of the molecular world using animations. *Chemistry Education Research and Practice, 7*(2), 141–159.
Tversky, B., Morrison, J. B., & Betrancourt, M. (2002). Animation: Can it facilitate? *International Journal of Human Computer Studies, 57*, 247–262.
Velázquez-Marcano, A., Williamson, V., Ashkenazi, G., Tasker, R., & Williamson, K. (2004). The use of video demonstrations and particulate animation in general chemistry. *Journal of Science Education and Technology, 13*, 315–323.
Venkataraman, B. (2009). Visualization and interactivity in the teaching of chemistry to science and non-science students. *Chemistry Education Research and Practice, 10*, 62–69.
Vermaat, J. H., Kramer-Pals, H., & Schank, P. (2003, October). *The use of animations in chemical education*. Paper presented at the International Convention of the Association for Educational Communications and Technology, Anaheim.
Whisnant, D. M. (1984). Scientific exploration with a microcomputer: Simulations for nonscientists (CS). *Journal of Chemical Education, 61*, 627.
Williams, M. D. (1996). Learner-control and instructional technologies. In D. Jonassen (Ed.), *Handbook of research for educational communications and technology* (2nd ed.). Mahwah: Lawrence Erlbaum Associates, Inc.
Williamson, V. M. (2008). The particulate nature of matter: How theory-based research can impact the field. In D. Bunce & R. Cole (Eds.), *Nuts and bolts of chemical education research*. Washington, DC: American Chemical Society.
Williamson, V. M. (2011). Teaching chemistry with visualizations: What's the research evidence? In D. Bunce (Ed.), *Investigating classroom myths through research on teaching and learning*. Washington, DC: American Chemical Society.
Williamson, V. M., & Abraham, M. R. (1995). The effects of computer animation on the particulate mental models of college chemistry students. *Journal of Research in Science Teaching, 32*(5), 521–534.
Winberg, M. T., & Berg, C. A. R. (2007). Students' cognitive focus during a chemistry laboratory exercise: Effects of a computer-simulated prelab. *Journal of Research in Science Teaching, 44*(8), 1108–1133.
Wu, H., Krajcik, J., & Soloway, E. (2001). Promoting understanding of chemical representations: Students' use of a visualization tool in the classroom. *Journal of Research in Science Teaching, 38*(7), 821–842.
Xie, Q., & Tinker, R. (2006). Molecular dynamics simulations of chemical reactions for use in education. *Journal of Chemical Education, 83*, 77.

Yang, E.-M., Andre, T., & Greenbowe, T. J. (2003). Spatial ability and the impact of visualization/animation on learning electrochemistry. *International Journal of Science Education, 25*(3), 329–349.

Yeung, A., Schmid, S., & Tasker, R. (2008). Can one version of online learning materials benefit all students? In A. Hugman & K. Placing (Eds.), *Symposium proceedings: Visualisation and concept development* (pp. 152–158). Sydney: UniServe Science, The University of Sydney.

Yezierski, E. J., & Birk, J. P. (2006). Misconceptions about the particulate nature of matter: Using animations to close the gender gap. *Journal of Chemical Education, 83*(6), 954–960.

Zare, R. (2002). Visualizing chemistry. *Journal of Chemical Education, 79*, 1290–1291.

From the Scientific to the Educational: Using Monte Carlo Simulations of the Microkosmos for Science Education by Inquiry

George Kalkanis

Introduction

The application of the "microkosmos model" in education, widely known as "particulate nature of matter," has been accepted in some cases while rejected in others, by researchers. To begin with, Nobel Prize laureate R. Feynman (1995) praises the contribution of the particle model in science and specifically in understanding the macrokosmos (or macrocosmos) through the microcosmos. Other researchers support that understanding particulate nature of matter is of great importance for students so as they may approach all branches of science (Bouwman-Gearhart et al. 2009). Wiser and Smith (2008) insist on students learning about particles as early in their education as possible (more specifically, at the end of primary school or at junior high school) because this helps them solidify their first understanding of matter and also provides an important base for the understanding of several macroscopic concepts, which are difficult to be approached in any other way but through the atomic molecular theory. The learning of the particulate nature of matter is useful, as well, in cases of working with phenomena where students lack observational data, like the case of invisible gases (Löfgren and Helldén 2009; Papageorgiou et al. 2010).

According to Chabay and Sherwood (1999), in the case of high-school students, focusing on the fact that matter is composed of atoms, as well as on the process of modeling physical systems, is more interesting and relevant to them than a repetition of a purely classical approach. In addition, Snir et al. (2003) demonstrated that students who understand how the properties of atoms and of molecules explain macroscopic phenomena, had also understood well, from a macroscopic perspective, the

G. Kalkanis (✉)
Department of Primary Education, Laboratory of Science, Technology and Environment, University of Athens, Athens, Greece
e-mail: kalkanis@primedu.uoa.gr; gkalkanis@gmail.com

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_14,

basic characteristics of matter (weight, volume, density). In a study with students of late primary or early high school, Hwang (2000) found that the conception of the particle model is evolving gradually at these ages. Furthermore, it was concluded that particulate nature of matter is one of the fundamental models of science.

Understanding the particulate model can be difficult for elementary and even secondary school students. Franco and Taber (2009) investigated the results of the application of a curriculum context, where “particles” was a key idea in the science courses for all 11–14-year-olds in the United Kingdom. The result of this study showed that only a minority of students had understood the basic particle theory at the end of this long course sequence. In the same direction, Löfgren and Helldén (2009) admit that their aim for teaching the particulate nature of matter was so that those students who wished could use particle models when considering changes in matter. In the case of university students, Thacker et al. (1999) found that most of the students whose instructional experiences included an emphasis on the development of models of microscopic processes developed a better understanding of the phenomena studied.

Many researchers agree that the early development of a simple particle model may – eventually – help students conceive a more complex subatomic particle model (Bouwman-Gearhart et al. 2009), since the understanding of a basic particle model by the students is necessary for them in order to approach the atomic structure, taught later (Papageorgiou and Johnson 2005, 2010). According to Eshach and Fried (2005), science taught in early school years is an effective frame for the development of scientific thought and is expected to contribute to the foundation of understanding difficult science concepts and phenomena, which will be studied later on in a more formal way.

In the case of Greece, after a special edition of the “Educational Model of Microkosmos” had been incorporated in the official handbooks for primary school pupils of 10–12 years old (Apostolakis et al. 2006), researchers investigated the influence that enhancing the teaching process with activities supported by information technologies had on teachers and pupils (Imvrioti 2011; Tzimos 2011). The results show that this model is appropriate for primary education, in the sense that microcosmos helps understand the macrocosmos, while understanding is improved by proper software. Other researchers’ investigations of junior high-school students’ understanding (Tsitisipis et al. 2011) or secondary and university students’ comprehension (Stefani and Tsaparlis 2009; Tsaparlis and Papaphotis 2002, 2009; Tsaparlis 1997; Vlahou et al. 2011) of the particulate nature of matter indicate the interest of the researchers on this subject, while their propositions are expected to improve teaching interventions and learning difficulties or to be useful in designing programs of studies.

Undoubtedly, further investigation is necessary in order to determine how to support students from their early school life in order to enable them to build a particle model by the age of 16 and be capable of applying it when explaining real, everyday situations (Löfgren and Helldén 2009).

We made the hypothesis that the understanding of the processes of microcosmos and the educational use of the model of microcosmos can be enhanced by the implementation of educational simulations, visualizations, and animations. In this chapter, we report results of an educational study that provided some support for this hypothesis.

Framework, Questions, Aims, and Research

The general framework of this research is to notice that science education aims merely at knowledge of phenomena and definition of concepts, while there is no important focus neither on the procedures which caused or led to these phenomena nor on the deeper understanding of these procedures. This kind of science education results not only to a superficial view of the natural world but also to the impression that science is fragmentary. In addition, it certainly does not provide any satisfactory link between science and science education, that is, it does not join scientific research with educational process in any of their basic characteristics: subject, methodology, and supporting software. On the contrary, we believe that nowadays science education should directly take advantage both of the scientific research results and of the methodology and supporting software that the research utilizes. More specifically, we support that education ought to take into account scientific findings about the structure, interactions, and motion of particles, as they are expressed by the "microcosmos model" of contemporary science, in order to explain with this knowledge of the microcosmos processes the physical, chemical, and biological phenomena of the macrocosmos. Furthermore, the use of the microcosmos model and microscopic explanations could unify the fragmentary view of science.

Our research questions are whether, and up to which degree, teachers, students, and pupils understand and use the microscopic model, after they have been taught about it through the scientific/educational methodology and by the use of educational software containing simulations and visualizations of that model.

The answers to these questions will help us to achieve three aims: first, the transfer of knowledge of microcosmos procedures from science to education, which is declared by science as a "scientific microcosmos model" and has been transformed by education to a "scientific/educational microcosmos model"; second, the configuration and application of the scientific research methodology to the "scientific/educational methodology by inquiry," which may be used at the educational procedure of science; third, the utilization of contemporary digital technologies both at the level of scientific research and that of educational procedure.

Our research included the following stages: (a) We began by modifying the scientific microcosmos model, and, thus, the microscopic structures, interactions, and motions are likely to be comprehended by students (of any level); (b) we then transformed the basic steps of scientific methodology to be feasible by students for science education; (c) we copied ideas and techniques of the microcosmos simulation and visualization from the scientific research and developed a dynamic educational software and static captures in order to offer students a visual simulation of the structure, interactions, and motion of the microkosmos particles; (d) we implemented the above software (and/or static captures) into the steps of "scientific/educational by inquiry methodology" during the educational procedure of all levels (primary, secondary, university, in-service teachers' training) so that students may be able to explain macroscopic phenomena by microcosmos processes; and (e) we evaluated this implementation.

From Scientific to Educational Simulations

For the educational simulations of the microcosmos, we used the Monte Carlo methods, which have been used with great success in elementary particle research. These statistical methods use sequences of random numbers to perform various calculations to simulate stochastic systems like "microcosmos." The structure, the interactions, and the movements of microcosmos – from the "a-toma"/superstrings (?) to molecules – are simulated and animated by a hands-on computer program, with the use of Monte Carlo methods and techniques since microcosmos is eminently a stochastic system. The used Monte Carlo techniques employ those methods in order to simulate and animate, by means of a computer, certain stochastic processes according to specific distributions (Kalkanis 1996, 1997). This way, the stochastic processes of microcosmos may contribute to explaining and predicting (the) phenomena of macrocosmos.

In science, Monte Carlo techniques have proven to be a powerful and irreplaceable tool for research, mainly in predicting and/or explaining experimental data (for a typical example, see Phillips et al. 1984; Kalkanis 1984).

In education, we may profit by the features of simulations and visualizations of the microcosmos too. These simulations and visualizations may offer a glimpse, even a view, of the details of the complex realistic systems operation of microcosmos with a pedagogical virtue. Furthermore, this characteristic of Monte Carlo simulation and animation programs is one of the characteristics which "legitimate" the use of computers in science education (Hadzidaki et al. 1998; Kalkanis and Sarris 1999).

On the other hand, microcosmos is the part of the world where the wave–particle duality comes up vigorously, and such computer simulations/animations may wipe out the impression or misconception, generally held by students, that "quantum mechanics is simply incomprehensible" and clarify some quantum "paradoxes" such as the paradox of wave–particle duality. In the animation program, designed and created in situ (Dimopoulos and Kalkanis 2003, 2004a, b, 2005, 2006, see simulations in http://microkosmos.uoa.gr (english version) → Science Education), the wave–particles are visualized by successive appearing and disappearing dots, without any display of track.

A relevant research (Drolapas and Kalkanis 2011) confirmed that the understanding of microscopic particles by students and teachers is better achieved when particles are shown with their interior structure, instead of particles bound by circles. Such images of atoms and molecules not bound by circles, that do not exist in any case, are shown in Fig. 1.

An imaginary journey into the interior of the matter offers students (and teachers) a glimpse of the microcosmos processes, which can then help to explain many

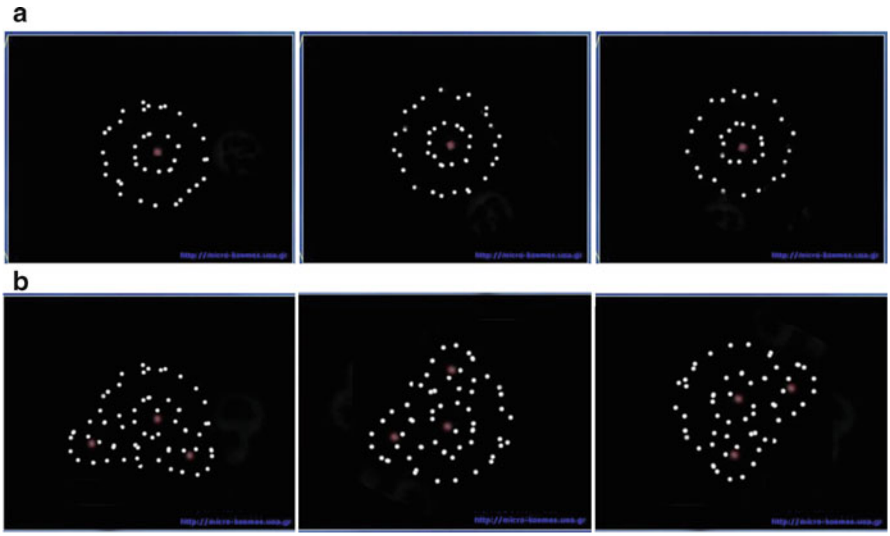


Fig. 1 (**a**) The wave–particles/electrons of an atom are shown in three successive captures of the atom, without any electron tracks and atom boundary. (**b**) Captures of a water molecule where its interior atomic structure is shown without any electron tracks and without any molecule boundary

macroscopic concepts and phenomena (e.g., excitation–relaxation of atom's electrons, emission of photons, molecules' interactions, rigidity of solids, molecules' thermal motion, expansion–contraction of matter, fluidity of liquids and gases, static pressure, and friction). The hands-on operation of an improved version of this computer simulation and animation program may offer the opportunity to students and teachers alike to change or select the parameters of the desired views of the microscopic processes (number of wave–particles, interactions, motion…) in order to correspond to certain macroscopic phenomena.

The dynamic educational simulations and visualizations of the microcosmos created with Monte Carlo techniques (at the Laboratory of Science, Technology, and Environment of the Department of Primary Education of the University of Athens) have been intergraded into independent digital presentations of normative, exemplary educational procedures and/or independent educational software for students of all grades and forms of education, as well as into episodes of educational television (Kalkanis et al. 2007). An example of this software is presented in Fig. 2, which display captures of the position and movement of molecules in solids, liquids, and gases, at two different temperatures.

As a consequence, the phenomenon of expansion of solids, liquids, and gases and the phenomenon of change of state from solid to liquid and to gas, when temperature rises, are explained. Other microscopic procedures that have been simulated or visualized in the frame of this scientific/educational research are the movements of the free electrons of a metal with or without electrical current. These movements explain not only the electrical current but also thermal and optical secondary phenomena.

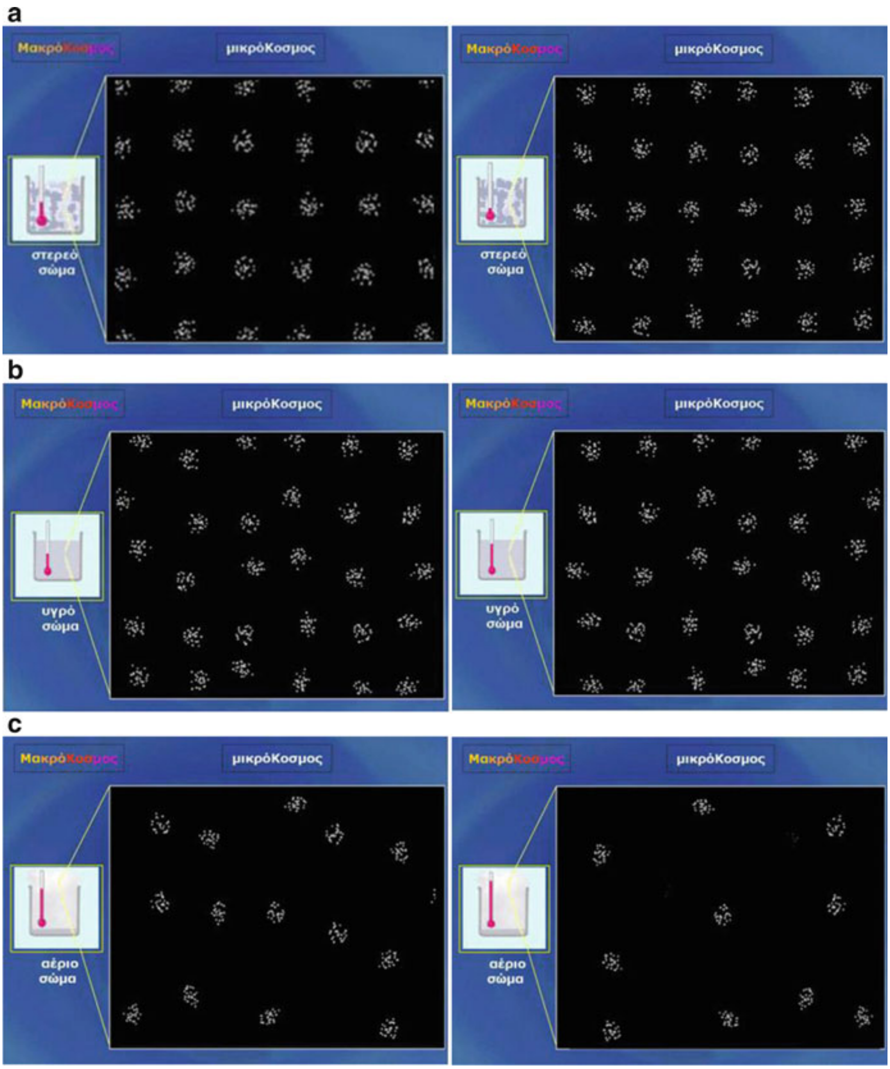


Fig. 2 (**a**) Captures of the dynamic simulations/visualizations of the positions and of movements of the molecules in a solid at two different temperatures. (**b**) Captures of the dynamic simulations/visualizations of the positions and of movements of the molecules in a liquid at two different temperatures. (**c**) Captures of the dynamic simulations/visualizations of the positions and of movements of the molecules in a gas at two different temperatures

Static pictures from these dynamic simulations/visualizations, like those depicted in Fig. 3, have been included in the official science handbooks that are published by the Greek Ministry of Education and are taught to students of the last two grades of primary education (Apostolakis et al. 2006, see http://micro-kosmos.uoa.gr (english version) → Science Education).

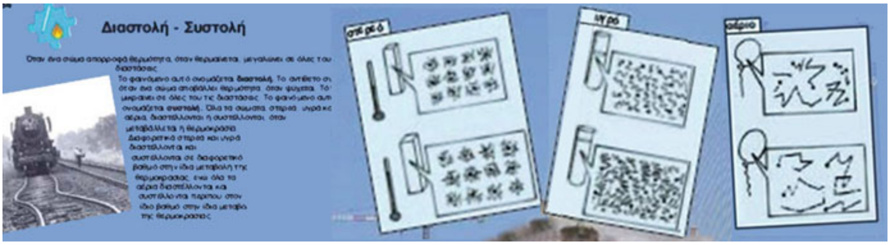


Fig. 3 The microscopic movements of the molecules of a solid, a liquid, and a gas are depicted at two different temperatures. These sketches explain the phenomenon of expansion of solids, liquids, and gases and consequentially the phenomenon of change of state, from solid to liquid and to gas when temperature rises

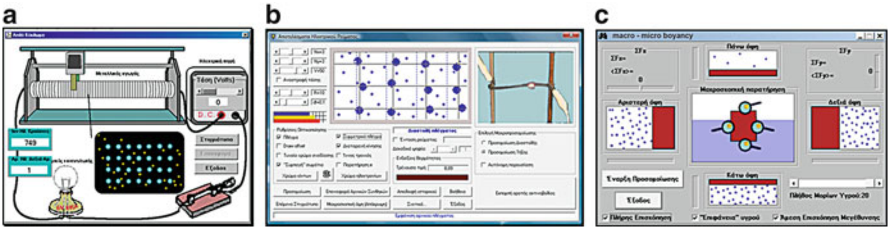


Fig. 4 (**a**–**c**) Captures of dynamic simulations/visualizations of microcosmos vs. macrocosmos

Figure 4 shows three examples of the relation of microscopic particles' movement to the corresponding macroscopic experiments, as presented by some dynamic simulations and visualizations of the microcosmos, which have been designed and created in situ as well (Kyriaki 1997; Tsakonas and Kalkanis 1998; Tsakonas et al. 2011; see simulations in http://micro-kosmos.uoa.gr (english version) → Science Education).

Figure 4a shows the thermal movements of free electrons and positive ions in a metallic conductor, with or without electrical current, along with simultaneous measurements of macroscopic physical quantities of the applied voltage and the current flow. At the same time, the number of collisions of free electrons, moving in all directions of the conductor along with the ions of the metallic conductor, is calculated and is compared with the values and the direction of current. The next figure (Fig. 4b) shows the changes of movements of electrons and ions of the metallic conductor, when current changes. These changes are combined with the macroscopic changes of the conductor, such as the change of temperature, the change of its length due to thermal expansion, and the change of state from solid to liquid, when temperature rises significantly. The last figure (Fig. 4c) shows the movement of air and liquid molecules around a solid, which is half-immersed in the liquid. The molecular collisions with the surface of the solid are then counted, and the static pressures and buoyancy force are calculated, from the macroscopic forces applied to the solid by the air and liquid on every surface.

The use of dynamic simulations instead of static captures of microcosmos is preferred by teachers, students, and pupils; however, we believe that both should be available and utilized during any educational procedure, since in some cases, systematically or occasionally, the use of digital technologies is not easy or possible.

From Scientific to Educational Methodology: The Research Study

The dynamic simulations and visualizations of the microscopic processes, as well as the static captures or sketches, have been integrated into the steps of scientific/educational method by inquiry. We formatted the scientific method of research into five simple and explicit steps: (a) trigger of interest, (b) hypotheses, (c) experimentation, (d) theory, and (e) continuous testing. We then adjusted each of them for students as steps of an educational method by inquiry for the educational procedure: (a) trigger of interest; (b) hypotheses; (c) experimentation; (d) conclusions, applications; (e) generalizations, explanation with microcosmos (Straga and Kalkanis 1999; Kalkanis 2007).

This scientific method was formatted by Newton; however, it originates from the ideas of Thales of Miletus, which were also used by other natural philosophers and early scientists in ancient Greece, for example, by Archimedes (Lloyd 1970). This method has been used since the ancient Greek philosophy era, and it is still used nowadays, in the context of modern science. It is believed that this scientific method not only helps the scientific research to be efficient and fruitful but also discriminates sciences from other fields of knowledge. To give an example of the use of this method in a modern scientific research and the way in which the various phases of the research were integrated into the five steps of this methodology, as described above, we can refer again to the procedure followed during the aforementioned study about proton decay, using the Harvard–Purdue–Wisconsin detector.

The scientific/educational by inquiry method, formatted into the five simple steps mentioned above, is used by all Greek students of 5th and 6th grade of primary education in science, in accordance with the official science handbook compiled by the Ministry of Education, as well as the in-service retrained and future teachers who studied at the University of Athens. During this research, we also integrated the educational simulations/visualizations of microcosmos into the steps of this methodology.

As an example of the employment of this scientific/educational method and the way in which we expect students to integrate the various processes into the five steps of the methodology, we present the worksheet for the topic “expansion/compression of matter” vs. “increase/decrease of temperature”.

Applications, Results, and Evaluation

The study was carried out by the Laboratory of Science, Technology, and Environment of the Department of Primary Education of the University of Athens during the academic years 2006–2010. There were three groups of participants:

(a) 200 in-service teachers, 84 of them receiving in-service training at the Marasleio Didaskaleio of the Department of Primary Education taking compulsory theoretical courses and practical teaching exercises at the Science Laboratory, as well as 116 teachers taking training seminars at Peripheral Educational Centers in Attica and in schools by school counselors.
(b) 600 undergraduate (2nd and 3rd year) university students of the Department of Primary Education taking compulsory theoretical courses and compulsory experimental exercises at the Laboratory of Science.
(c) 300 fifth-grade primary education pupils (10–11 years old) in science classes, before being taught the relevant phenomena.

All participants spent (in their usual classroom) 4 h on selected thematic units performing (in groups of three) experiments concerning materials' expansion/compression as well as change of state, watching and interacting with the relevant educational software, completing worksheets, and recording their observations. The experiments were performed by the participants themselves, and the role of instructors was purely supportive. The educational process was organized according to the aforementioned steps of the scientific/educational methodology by inquiry. An example of the worksheets and experiments is shown in Fig. 5.

Written questionnaires were given to the participants before and after the 4-h intervention, and the participants' worksheets were then analyzed. The questionnaires included questions about the following: (a) the explanation of macroscopic properties (volume, shape, and rigidity or viscosity) of materials, based on the position and micro-movements of their particles/molecules; (b) the explanation of the change of dimensions (expansion or compression) of solids, liquids, and gases; and (c) the explanation of the change of state of the materials (to or from solid, liquid, and gas) when the temperature changes, which was also based on the micro-movements of their particles (molecules).

The participants' (teachers, students, pupils) performance was characterized as "inadequate" (when answering adequately less than half of the questions), "adequate" (when answering adequately more than half of the questions), "complete" (when answering adequately all the questions), and "excellent" (when answering completely all the questions providing the correct microscopic explanations). After defining these marking criteria, three graders evaluated the participants' answers without knowing which group the participants belonged to or whether they were completed before or after the intervention.

The results (expressed as percentages) in all three categories of responses, before and after the educational process, are presented in bar diagrams form in Figs. 6, 7, and 8.

Focusing on the category of "inadequate": performance (less than 50 % of correct answers), we notice that the great majority of teachers had less than 35 % of correct answers, of students less than 22 %, and of pupils less than 13 %.

The participants' performance was marked as 1 when it was "inadequate," 2 when it was "adequate," 3 when it was "complete," and 4 when it was "excellent." The scores of participants pretests and posttests in each case (teachers, students, and pupils) were subjected to paired-samples *t*-test, which showed statistically significant differences ($p<0.001$) between pre- and posttest scores in each case, in favor of the latter.

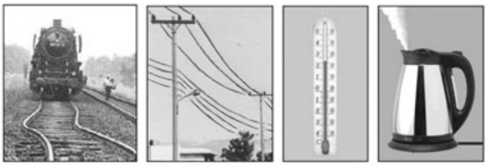
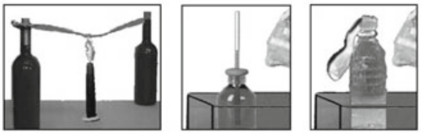
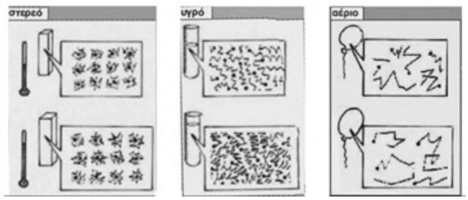
Trigger of interest	Observe these pictures, describe the phenomena and correlate the dimensions of some materials with the temperature 
Hypothesis	Hypothesize about the correlation of materials' dimension and temperature and explain the phenomena (A typical and usual explanation): "*I believe this happens because the volume of the molecules that make the material increases when the material is heated*" 
Experimentation	Perform experiments of heating and cooling different materials (solids, liquids, gasses) and observe carefully what happens 
Conclusions – applications	Derive conclusions from your observations about the heating/cooling of a material vs. its expansion/compression, and apply the findings to the phenomena used for triggering and explain them (An expected conclusion): "*I conclude that the heating/cooling of a material causes its expansion/compression, however, despite the detailed observation of the experimental process, I cannot make any conclusion regarding the cause of a material's expansion/compression with increase/decrease of the temperature and confirm or reject any hypothesis …*"
Generalization – explanation with micro-cosmos	Watch carefully relevant static captures, like those depicted below (and/or relevant dynamic simulations/visualizations like those shown in Fig. 2a, b, c)  (An expected explanation): "*The expansion/compression is based not on the change of the volume of molecules but on the increase/decrease of movement of molecules (consequently, they fend off/approach each other)*"

Fig. 5 Worksheet for the topic "expansion/compression of matter" vs. "increase/decrease of temperature"

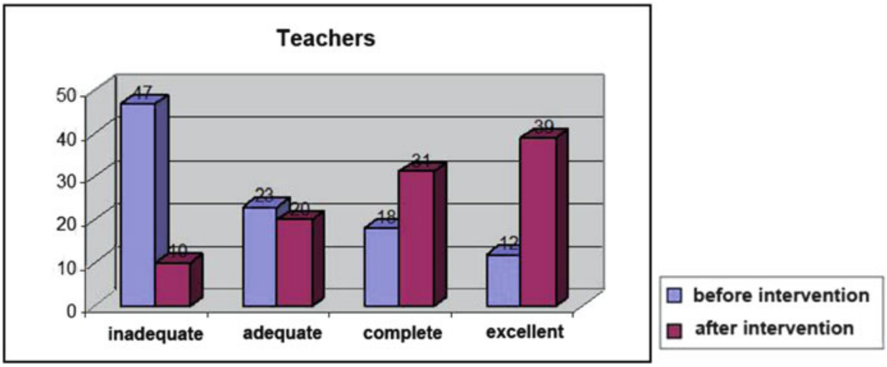


Fig. 6 The percentages of teachers' responses, before and after the educational process

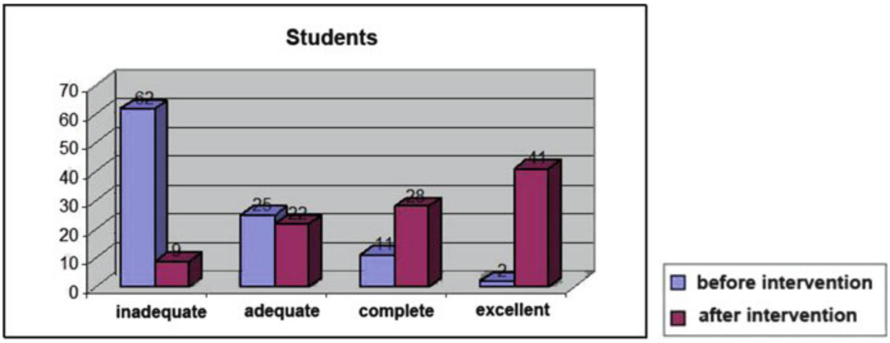


Fig. 7 The percentages of students' responses, before and after the educational process

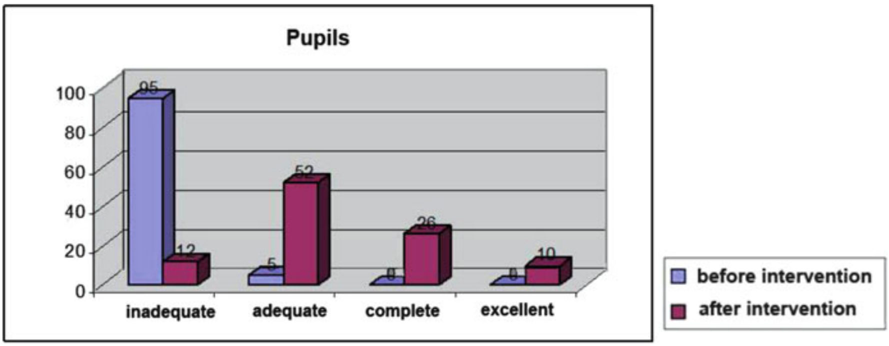


Fig. 8 The percentages of pupils' responses, before and after the educational process

Teachers: $t(199) = -21.211$; $p < 0.001$ (means: pretest =1.95/4 and posttest = 2.99/4, std. deviations: pretest =1.065 and posttest = 0.997).
Students: $t(599) = -49.774$; $p < 0.001$ (means: pretest =1.53/4 and posttest = 3.01, std. deviations: pretest =0.768 and posttest = 0.996).
Pupils: $t(299) = -30.190$; $p < 0.001$ (means: pretest =1.05/4 and posttest = 2.34/4, std. deviations: pretest = 0.218 and posttest = 0.816).

These *t*-test results prove the effectiveness of the intervention in all categories of participants.

Conclusions and Implications

We think that the above results of the evaluation are (at least) encouraging, and we suggest the generalization of creating such educational software covering more areas of science as well as broadening its use to more teachers, students, and pupils.

Based on the questionnaires, both teachers and university students understood the particulate structure of matter, correlating the microscopic processes with macroscopic phenomena. In addition, according to their comments in the worksheets, they felt confident that they could use the microcosmos model to explain macroscopic phenomena to their pupils (76 % of teachers and 54 % of university students/prospective teachers).

The elementary school pupils understand the particulate nature of matter less well but made efforts to connect the microscopic processes with the macroscopic phenomena, providing in some cases explanations where macroscopic properties and microscopic processes were confused. We are of the opinion that the results reflect mostly the use of the software. In the case of material and software, the instructors did not encounter any such difficulties in the implementation process. Moreover, in regard to material, software, methodology, and structure of the program, the research confirmed the feasibility and effectiveness of their application, since the participants' performance was improved significantly after the intervention, as shown by the above statistical analysis.

Therefore, we suggest the continuation and generalization of the application of this kind of programs, with additional information, material, software, and processes, especially with processes that are both attractive to and effective on pupils. This will lead to the optimization of the educational and instructive role of the microscopic model, which not only extends science education to contemporary scientific theories but also contributes to a deeper comprehension and interpretation of physical phenomena of everyday life.

Acknowledgments Acknowledgments go to my students Panayiotis Tsakonas, Vasilis Dimopoulos, and Eleni Kyriaki for creating the simulation animation programs during their doctorate theses. I would also like to thank Despoina Imvrioti, Sofia Stragka, and Ourania Gikopoulou for implementing the evaluation of the programs, and finally all my students for their cooperation.

References

Apostolakis, E., Panagopoulou, E., Savas, S., Tsagliotis, N., Makri, V., Pantazis, G., Petrea, K., Sotiriou, S., Tolias, V., Tsagkogeorga, A., Kalkanis, G. (2006). *Official science handbooks for the 5th and 6th grade of primary education "Science – I Investigate and Discover" (in Greek)*. Athens: Greek Ministry of Education – Institute. Available at: http://www.pi-schools.gr/books/dimotiko/ or at http://digitalschool.minedu.gov.gr/courses/DSDIM-E107/)

Bouwman-Gearhart, J., Stewart, J., & Brown, K. (2009). Student misapplication of a gas-like model to explain particle movement in heated solids: Implications for curriculum and instruction towards students' creation and revision of accurate explanatory models. *International Journal of Science Education, 31*(9), 1157–1174.

Chabay, R., & Sherwood, B. (1999). Bringing atoms into first-year physics. *American Journal of Physics, volume, 67*, 1045–1050.

Dimopoulos, V., & Kalkanis, G. (2003, August 19–23). *An introduction of microcosmos quantum model to students of limited mathematics and science background supported by computer simulations/visualizations*. In 4th ESERA Conference, "Research and the quality of science education", Noordwijkerhout.

Dimopoulos, V., & Kalkanis, G. (2004a, July 19–23). *Quantum physics for all – Using ICT to experiment and simulate quantum principles*. In International Conference of GIREP 2004 "Teaching and Learning Physics in New Contexts", Ostrava. Available at: http://girep.org/proceedings/proceedings.html?volume=8

Dimopoulos, V., & Kalkanis, G. (2004b, August). *Science instruction with the use of information communication technologies – Suggestions and applications of quantum approaches*. In European Conference on Research in Science Education (E.S.E.R.A.) – Summerschool, University of Duisburg-Essen, Duisburg/Essen. Available at: http://micro-kosmos.uoa.gr (English version) → Publications

Dimopoulos, V., & Kalkanis, G. (2005, August 28–September 1). *Simulating quantum states of the atom of hydrogen – A simulation program for non-physics major's students*. In European Conference on Research in Science Education (ESERA), Barcelona. Available at: http://naserv.did.gu.se/ESERA05/cd/pdfs/eBook.pdf#page=548

Dimopoulos, V., & Kalkanis, G. (2006, September 4–9). *Hands-on spectrum lines – Introducing microscopic quantum explanations of the emitted photons to non-physics major's students*. In HSCI 2006, 3rd International Conference on Hands-on Science, "Science Education and Sustainable Development", University of Minho, Braga. Available at: http://micro-kosmos.uoa.gr/Hands-on-Science/presentations/326/Braga_Dimopoulos_Kalkanis_back.ppt

Drolapas, A., & Kalkanis, G. (2011, 15–18 April). *An inquiry process of electing an educational model of the atom that would be valid for simulations of physical phenomena*. In 7th Greek National Conference on Science Education and New Technologies in Education Interactions between Research and Practice in Science Education, University of Thrace, Alexandroupolis. Available in Greek at: http://www.7sefepet.gr/images/stories/pdf/7sefepet-praktika.pdf and in English at: http://micro-kosmos.uoa.gr (English version) → Publications

Eshach, H., & Fried, M. (2005). Should science be taught in early childhood? *Journal of Science Education and Technology, 14*(3), 315–336.

Feynman, R. (1995). *Six easy pieces*. Reading: Addison-Wesley, California Institute of Technology.

Franco, A. G., & Taber, K. S. (2009). Secondary S students' thinking about familiar phenomena: Learners' explanations from a curriculum context where 'particles' is a key idea for organising teaching and learning. *International Journal of Science Education, 31*(14), 1917–1952.

Hadzidaki, P., Stavrou, D., & Kalkanis, G. (1998). *The simulation/visualization of the accepted physical models of the microcosmos, as an instructional tool. The hydrogen atom orbitals (in Greek)*. In 1st Greek Conference on Science Education, Thessaloniki.

Hwang, B. T. (2000, August). *Students' understandings and misconceptions of particulate natures in gaseous phase and their science achievement*. In Proceedings of the International Conference of Groupe International de Research sur l' Enseignement de la Physique, Barcelona.

Imvrioti, D. (2011, 15–18 April). *Microkosmos in children's world – Activities with ICT for the particular nature of matter for 5th grade of primary education*. In 7th Greek National Conference on Science Education and New Technologies in Education Interactions between Research and Practice in Science Education, University of Thrace, Alexandroupolis. Available in Greek at: http://www.7sefepet.gr/images/stories/pdf/7sefepet-praktika.pdf and in English at: http://micro-kosmos.uoa.gr (English version) → Publications

Kalkanis, G. (1984). *Construction, calibration and first results of Harvard–Purdue–Wisconsin detector for proton decay* (in Greek), Ph.D. thesis, University of Athens, Athens.

Kalkanis, G. (1996, August). *The Monte Carlo techniques as a tool in physics education – Applications to microcosmos processes* (invited workshop). In 1996 GIREP-ICPE Conference: "New ways of teaching Physics", Ljubljana. Available at: http://micro-kosmos.uoa.gr (English version) → Publications

Kalkanis, G. (1997, August). *Realistic systems/microkosmos, stochastic processes, probabilistic modelling, computer simulation/animation – (or) How to optimise understanding/teaching and learning real physical phenomena – An appeal and applications*. In 7th European Conference for Research on Learning and Instruction (E.A.R.L.I.), Athens. Available at: http://micro-kosmos.uoa.gr (English version) → Publications

Kalkanis, G. (2007). *Primary science education (I. The theories, II. The phenomena), Educational technologies and applications (I. The laboratory, II. The technologies)* (in Greek). Laboratory of Science, Department of Primary Education, University of Athens, Athens.

Kalkanis, G., & Sarris, M. (1999). An educational MONTE CARLO simulation/animation program for the cosmic rays muons and a prototype computer-driven hardware display. *Journal of Computers in Mathematics and Science Teaching, 18*(1), 61–80.

Kalkanis, G., et al. (2007). *Episodes for the Greek national educational television "microkosmos explains …1. heat and temperature, 2. evaporation, boiling and liquefaction, 3. melting and freezing, 4. friction, 5. renewable energy sources"* (in Greek). Athens: Greek Ministry of Education. http://www.edutv.ypepth.gr

Kyriaki, E. (1997). *An educational programming environment and educational software open to interventions by educators and students aiming at the reproduction and reconstruction of physical phenomena with the use of Monte Carlo simulations of microcosm* (in Greek). Doctorate Thesis, Supervisor Prof. G. Kalkanis, Department of Primary Education, Athens University, Athens.

Lloyd, G. E. R. (1970). *Early Greek science: Thales to Aristotle*. New York: W.W. Norton.

Löfgren, L., & Helldén, G. (2009). A longitudinal study showing how students use a molecule concept when explaining everyday situations. *International Journal of Science Education, 31*(12), 1631–1655.

Papageorgiou, G., & Johnson, P. M. (2005). Do particle ideas help or hinder pupils' understanding of phenomena? *International Journal of Science Education, 27*(11), 1299–1317.

Papageorgiou, G., Grammaticopoulou, M., & Johnson, P. M. (2010). Should we teach primary pupils about chemical change? *International Journal of Science Education, 32*(12), 1647–1664.

Phillips, T., Matthews, J., Aprile, E., Cline, D., Gaidos, J., Giboni, K., Kalkanis, G., Loveless, R., March, R., McHenry, R., More, A., Negret, J., Palfrey, T., Rubbia, C., Sembroski, G., Wilson, C., Winn, D., & Worstell, W. – HPW Collaboration. (1984). "A search for nucleon decay with multiple muon decays" by Harvard-Purdue-Wisconsin Detector. *Physics Letters B, 224*, 348–352.

Snir, J., Smith, C., & Raz, G. (2003). Linking phenomena with competing underlying models: A software tool for introducing students to the particulate model of matter. *Science Education, 87*, 794–830.

Stefani, C., & Tsaparlis, G. (2009). Students' levels of explanations, models, and misconceptions in basic quantum chemistry: A phenomenographic study. *Journal of Research in Science Teaching, 46*, 520–536.

Straga, S., & Kalkanis, G. (1999). *The scientific method enhanced by systemic analysis –field-work – Educational material – Information technologies, as a sequence of supportive approaches in present and future environmental education*. In International Conference on Environmental Education for Sustainable Future, Indian Environmental Society, New Delhi.

Thacker, B. A., Ganiel, U., & Boys, D. (1999). Macroscopic phenomena and microscopic processes: Student understanding of transients in direct current electric circuits. *American Journal of Physics, 67*, S25–S31.

Tsakonas, P., & Kalkanis, G. (1998). *A common technological applications trigger for teaching/learning physics by computer simulation programs*. In 3rd Multimedia in Physics Teaching and Learning Workshop, University of Sciences and Technologies of Lille, Lille. Available at: http://micro-kosmos.uoa.gr (English version) → Publications

Tsakonas, P., Gikopoulou, O., & Kalkanis G. (2011, 15–18 April). *Simulations/correlations between microscopic oscillations and macroscopic waves with the use of educational software – A preliminary version, application and evaluation.* In 7th Greek National Conference on Science Education and New Technologies in Education Interactions between Research and Practice in Science Education, University of Thrace, Alexandroupolis. Available in Greek at: http://www.7sefepet.gr/images/stories/pdf/7sefepet-praktika.pdf and in English at: http://micro-kosmos.uoa.gr (English version) → Publications

Tsaparlis, G. (1997). Atomic orbitals, molecular orbitals and related concepts: Misconceptions and difficulties in understanding among chemistry students. *Research in Science Education, 27*, 271–287.

Tsaparlis, G., & Papaphotis, G. (2002). Quantum-chemical concepts: Are they suitable for secondary students? *Chemistry Education Research and Practice, 3*, 129–144.

Tsaparlis, G., & Papaphotis, G. (2009). High-school students' conceptual difficulties and attempts at conceptual change: The case of basic quantum chemical concepts. *International Journal of Science Education, 31*, 895–930.

Tsitisipis, G., Stamovlasis, D., & Papageorgiou, G. (2011, 15–18 2011). *The principal components of students' understanding of the particulate nature of matter and its changes of state* (in Greek). In 7th Greek National Conference on Science Education and New Technologies in Education Interactions between Research and Practice in Science Education, University of Thrace, Alexandroupolis. Available at: http://www.7sefepet.gr/images/stories/pdf/7sefepet-praktika.pdf

Tzimos, E. (2011, 15–18 April). *Solids expansion and static electricity – Fifth grade student's apprehension with the use of a model of the particular nature of matter and educational software* (in Greek). In 7th Greek National Conference on Science Education and New Technologies in Education Interactions between Research and Practice in Science Education, University of Thrace, Alexandroupolis. Available at: http://www.7sefepet.gr/images/stories/pdf/7sefepet-praktika.pdf

Vlahou, A., Pantazi, G., Tsaparlis, G., Shwartz, Y., Ben-Zvi, R., & Hofstein, A. (2011, 15–18 April). *Evaluation of the level of chemical literacy in Greek secondary education: The case of the understanding of concepts in macroscopic and molecular level* (in Greek). In 7th Greek National Conference on Science Education and New Technologies in Education Interactions between Research and Practice in Science Education, University of Thrace, Alexandroupolis. Available at: http://www.7sefepet.gr/images/stories/pdf/7sefepet-praktika.pdf

Wiser, M., & Smith, C. (2008). Teaching about matter in grades K-8: When should the atomic-molecular theory be introduced? In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (pp. 205–240). New York/London: Routledge Taylor and Francis Group.

Part IV
Chemical Reactions, Chemical Phenomena

Can Simple Particle Models Support Satisfying Explanations of Chemical Changes for Young Students?

George Papageorgiou

Introduction: Explanations of Chemical Changes

Over the last decades, an increasing number of scientific works concerning science education refer to students' explanations of phenomena. Among them, there are a number of cases where simple descriptions or other similar kinds of students' responses to relevant questions have been categorized as explanations. However, an explanation of a phenomenon is more than such a simple response. As Taber and Watts (2000) reported, although usually the actual wording of a question seeking an explanation focuses on "how something happens," the emphasis is in fact on "why something happens." Further to this, Berland and Reiser (2009) suggest that an explanation of a chemical phenomenon should be an attempt to provide sufficient information that can specify: (a) *what* happens during the phenomenon, (b) *how* this can happen, and (c) *why* this phenomenon happens. In any case, an explanation of a chemical change should be considered as something more than a simple description of the change.

However, students usually answer only the first question ("what"), describing the whole phenomenon at the macroscopic level. Even when additional answers to the other two questions ("why" and "how") are provided, the whole context of the explanation remains very often at the macroscopic level (Hatzinikita et al. 2005). The macroscopic features of a chemical phenomenon are very useful indeed, since they provide indications about *what* changes occur (e.g., about the identity of the substances that appear or disappear), but they are not adequate to really explain the change. Genuine explanations of chemical changes need to involve also the submicroscopic level (Johnstone 2000). Since a chemical change means changes in the

G. Papageorgiou (✉)
Department of Primary Education, Division of Science and Mathematics,
Democritus University of Thrace, Alexandroupolis, Greece
e-mail: gpapageo@eled.duth.gr

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_15,

structure of the substances that are involved, a rationale based on the submicroscopic nature of these substances is needed to support the whole explanation. As a result, a particular model describing the structure of the substances at the submicrolevel should be used in order to have a satisfying explanation.

Working for satisfying explanations, science educators have consequently to use such models, taking in fact also into account the abilities of the students to participate in a procedure where three conditions are involved concerning:

1. The ability to evaluate the macroscopic features of a chemical change
2. The ability to work in submicroscopic terms
3. The ability to connect macro- and submicro-situations to each other

The first one is related to the students' ability to evaluate appropriately the macroscopic features of a chemical change. This is directly connected to students' experiences in observing, studying, and generally dealing with phenomena in the real world. Since, in practice, the engagement of students with chemical changes is not so easy, mainly due to the complexity of such changes, opportunities for more experiences in chemical changes through appropriate practical work (hands-on activities, lab experiences, etc.) are highly appreciated.

The second condition is related to the ability of students to work in submicroscopic terms. This means that students have to learn how to approach submicro-situations, how to work with their characteristics, and how to evaluate them in order to arrive at valuable information for reaching an interpretation. Here, the question is: What are the features of the submicrolevel that we would like to be involved in a particular case of a chemical phenomenon? Since an exploration of submicro-situations of substances can take place in a range of educational levels and in the context of different curricula, the corresponding complexity of that exploration can also vary accordingly. In other words, the particular model to be used in order to satisfactorily describe submicro-situations should be in accordance with the ability of students to work between its contexts.

There is also a third condition, which is related to students' ability to connect macro- and submicro-situations to each other so that they cooperate as a system. That is, students need to appropriately use a particular model for submicro-situations in order to decode the macroscopic indications and also to use the macroscopic indications in order to reinforce submicroscopic reasoning. In other words, the ability to successfully work separately in each one of these two levels (macro- and submicro) cannot warrant a satisfying explanation of a phenomenon. This is suggested by a number of studies (e.g., Franco and Taber 2009), which have shown that the understanding of the particulate nature of the substances to a certain degree does not necessarily result in an appropriate use for explanations of relevant phenomena. Further to these studies, in a recent work on 6th grade pupils' explanations of chemical changes (Papageorgiou et al. 2010), results showed that a satisfying explanation of chemical change had as precondition the development of particle ideas to a high level, but the opposite was not always true, i.e., only a number of those who developed particle ideas to a high level could also explain satisfactorily the chemical changes.

As a result, the importance of students' ability to connect particular model for submicro-situations to macro-situations should be acknowledged by the science curricula.

However, since an explanation of a chemical change is connected to a particular model for the structure of the substances that are involved, the features of this model determine the features of the corresponding explanation. In Greece, for example, a model for the description of the structure of the substances is introduced in 5th grade (ages 10/11). According to this model, matter is made up of small particles, namely, molecules and atoms, whereas atoms consist of protons, neutrons, and electrons (Greek Pedagogical Institute 2003). Although pupils in primary education do not work about explanations of chemical changes, this particular model determines the first attempt of junior high school students (ages 13/14) to explain chemical phenomena at the submicrolevel, in the context of atoms reordering of the preexisting substances. Later on, Greek students of high school (ages 15/16) reconsider the formation of new substances during chemical phenomena in a more sophisticated way, where subatomic particles are involved, in the context of a model for the structure of the atom based on the Bohr model. Similarly, in the national curriculum for England, the model supporting that matter is made up of particles and is introduced in level 6 (age 11), but students work in fact on this model for possible explanations of chemical phenomena in level 8 (DfES 2003). In higher levels, explanations of chemical phenomena become more satisfying, as the corresponding models for the structure of the substances change to more sophisticated ones.

Levels of Explanations for Chemical Changes

Taking into account the above, one may argue that the meaning of a satisfying explanation of a chemical change is not something that is stable, since it depends on the corresponding model that is used for the description of the structure of the substances involved. However, the difficulty of such models can significantly vary as it depends on the features and generally on the whole context that are usually connected to the educational level where the model refers to. As a result, explanations of chemical changes can also vary in accordance to the educational level of the learner. In other words, we cannot expect from a pupil of primary education to work at the same context of explanation as one at which a student of tertiary education will probably operate. But of course, this does not mean that we can never characterize an explanation of a primary pupil as a satisfying one – we just have to take into account its educational level.

Speaking from the science education researchers' perspective, we could say that there are a significant number of such models supporting corresponding contexts for explanations of chemical changes, which have been developed or studied for particular educational levels. Although it is difficult to put such models and explanations into particular frames, we could possibly categorize them in three very general levels. Thus, we could present this categorization in the form of Table 1. In that

Table 1 A general categorization for the basic features of models and corresponding explanations concerning chemical changes

Level	Model describing the structure of substances (basic features)	Explanation of chemical changes (basic features)
1st	Introduction of the "atom" as an important kind of particle and the "bond" as a "kind of holding" between atoms	New substances are formed [*what*] due to the atoms reordering of the preexisting substances [*why*] as bonds are broken and new bonds are formed [*how*]
	The idea of the "molecule" could also be used	*Emphasis on the idea of chemical change itself in terms of atoms reordering*
2nd	Representation of the structure of the atom as nucleus and electron shells (electronic configuration based on the Bohr model)	New substances are formed [*what*] because structural characteristics of the atoms/ions of the substances change [*why*] as bonds are broken, structures destroyed, and new bonds and structures are formed [*how*]
	The new entity of "ion" is emerged	
	Substances could be either "molecular" or "nonmolecular"	*The chemical change in terms of more kinds of particles involving subatomic structure*
	Bonds could be categorized as covalent, ionic, metallic, etc.	
3rd	Representation of the structure of the atom based on orbital ideas – atomic and molecular orbitals	New substances are formed [*what*] due to mechanisms within orbital ideas that lead to the changes of substances – a probabilistic approach to how and why a reaction happens [*why*] [*how*]
		The chemical change in terms of orbital changes

table, there are two columns, one referring to the basic features of the models that describe the structure of the substances and one referring to the basic features of the explanations that are based on the corresponding models, and three lines, one for each level. Of course, this is a very general categorization and one could distinguish sublevels in each one of these levels.

At the 1st level, explanations of chemical changes are based on the concept of the atom, whereas subatomic particles are not involved. In this context, Andersson (1986) categorized pupils' ideas about chemical changes into five categories, introducing, among them, a category for "answers acceptable from the chemistry teachers' point of view" as "chemical interaction." In that category, the corresponding acceptable answers were those referring to the "changes in the combination of atoms while the atomic identity is conserved." Also, Johnson (2002), in a study concerning explanations of chemical changes and after a series of relevant lessons over 3 years, categorized pupils' explanations of the formation of copper oxide (from copper and oxygen) in three categories. In the most satisfying of those (namely, category C according to Johnson), pupils could explain the change as a combination of two substances in order to form a new one in its own right using the idea of an atom, whereas they also used the idea of a molecule in another case where water was formed. Generally, in explanations of this (1st) level that could be characterized as satisfying, any changes in the properties of substances (macro-level) are directly connected to the corresponding changes in the ordering or holdings of their atoms (submicrolevel). The idea of "bond" is present as the strong holding between atoms, and the new structure that results when atoms are bonded together is usually introduced as a new kind of particle, that of the "molecule."

In the 2nd level, descriptions at the subatomic level, mainly based on the Bohr model, can provide possibilities for more sophisticated explanations. However, explanations of chemical changes at this level are usually problematic for the students, as they retain a number of nonscientific conceptions (Chandrasegaran and Treagust 2008). For Cokelez et al. (2008), the problems in students' explanations originate from the "ontological priority" of the atom and the transfer of the "conservation principle" to the atomic and molecular level. In other words, on the one hand, the atom seems to play the central role in students' explanations of chemical changes, and the ion is considered as an altered atom and the molecule as a sum of atoms, whereas on the other hand, the atom and the molecule remain the same after the change. As a result, it is of great importance for this 2nd level of explanations an appropriate manipulation of the concepts of the ion and the molecule as fundamental entities as the atom (Taber 2001), as well as the consideration of the structure of a substance either as molecular or nonmolecular. According to Johnson and Papageorgiou (2010), the differentiation between molecular and nonmolecular substances could be based on the idea of a "giant structure" in nonmolecular substances, where the entities of atoms (for the metallic structure) or ions (for the ionic structure) are its main components, in contrast to the concept of the "molecule," which is the fundamental entity for the structure of the molecular substances. Introducing these two types of structures of substances equally from the beginning of the 2nd level, there are many possibilities to counteract any students' thoughts regarding the existence of molecules in nonmolecular (e.g., ionic) structures. In any case, in a satisfying explanation at this 2nd level, changes of substances in a particular chemical change would be explained on the basis of discrete kinds of bonds (covalent, ionic, and metallic) and discrete structures (molecular or nonmolecular).

In the 3rd level, explanations of chemical changes are put into a new framework due to the probabilistic nature of the quantum mechanics. However, students, even of the higher education, find the concept of an orbital, either atomic or molecular, as difficult one, and they do not usually develop explanations at this level. As Tsaparlis and Papaphotis (2009) reported, students prefer to construct their explanations on the basis of more concrete models (like that of the 2nd level of explanation) using preexisting knowledge or to construct hybrid models using elements from simpler models. However, probabilistic models of the structure of substances that have been developed using quantum ideas have higher explanatory power, and they can explain or even predict the process of a chemical reaction to the highest degree. In a satisfying explanation at the 3rd level, the mathematical features of quantum ideas could justify the formation (or not) of a new bond in terms of bonding (or antibonding) molecular orbitals, and, therefore, they can provide new dimensions concerning the formation of new substances during a chemical change.

A Closer Look at the 1st Level of Explanations of Chemical Changes

Although each of the three levels of explanations has its own importance, the first one is probably the most important one in educational terms due to the fact that this is the level of pupils' first engagement with the idea of the chemical change and so forms the foundation for the next levels. Any inappropriate approach of the idea of chemical change at this level would probably have consequences in its approach during the next levels. Besides, at this 1st level, the emphasis is on the idea of the chemical change itself in terms of changes at the submicroscopic level in connection to the real world. Consequently, possible explanations at this level should be based on models, the features of which have to be carefully designed. These models are in fact particle models, since they are based on the particle theory, which are associated with the concept of "substance" (Johnson 2002) and not with the general idea of "matter" as the curricula for Greece and England support (see relevant reference in the "Introduction").

Since in chemical phenomena changes in pure substances occur, the design of such models has as precondition the establishment of the concept of substance and the clear distinction between "substance" and "mixture." It is important for the students to understand that any reference to particles concerns particles of particular substances and not particles in general. Furthermore, these particle models should offer a realistic framework for sufficient explanations, without gaps or problematic deviations from the epistemological truth, but also limiting possibilities for contradictions in the future (in higher grades of science education). Such a model could be based on some relevant key premises recently presented in the literature (Johnson and Papageorgiou 2010; Papageorgiou and Johnson 2005; Papageorgiou et al. 2010), the basic features of which are as follows:

1. The *atom* is introduced as a very important kind of particle, which is not connected to only one substance – the same atom can be found in many substances. Thus, we can use the atom as a "link" between preexisting and new substances during chemical changes.
2. The "atom" has a number of submicroscopic features, which are not associated with any macroscopic characteristic, such as the behavior and arrangement of atoms as a collection change during chemical changes, but their identity does not change during any physical or chemical change. (In contrast to the 2nd and 3rd levels of explanations, the idea of the *ion* is not introduced, since it is too difficult for this level.)
3. The idea of the *bond* is introduced: The general idea of "holdings" between particles (Johnson and Papageorgiou 2010) is specified as "bonds," which are only the strong kind of holdings that can "hold on" atoms together as one new entity (that of the "molecule," see next premise), whereas the weak holdings between molecules are introduced as *intermolecular forces*. Kinds of bonds (covalent, ionic, metallic, etc.) could not be supported here.

4. The idea of the *molecule* is introduced as the entity that results due to the bonding that keeps a particular small number of atoms together as one (if the number of atoms becomes big, then a giant structure could be formed). In contrast to the atom, the molecule is directly connected to only one substance.

As a result, this particle model can help students to explain chemical changes on the basis of the changes of bonds: *During chemical changes both formation and destruction of bonds happen*. Thus, in case of "molecular structures," explanations could involve the molecule as a second type of particle, whereas in case of "nonmolecular substances," explanations could be based on the concept of the atom (in fact, working inside the "repeated unit" of a giant structure). Of course, working in terms of atoms in nonmolecular substances, there is the risk for students to involve the idea of the "molecule." This is in fact a reason for supporting the explicit distinction between molecular and nonmolecular substances at as early a point as possible. Also, it should be acknowledged that, in this case (of nonmolecular substances), it is unavoidable, to a certain degree, for students to consolidate the idea of the atom instead of the "ion." However, when the introduction of the particle theory has been done through an appropriately designed particle model, and the idea of a "particle" is clear for the students (Johnson and Papageorgiou 2010), the "ion" could be introduced later on as a third kind of particle.

In any case, whether molecular or nonmolecular, an explanation of a chemical change is directly connected to an ability to work with the structure of substances at the submicroscopic level, and thus, any attempt to provide satisfying explanations in this 1st level should follow the understanding of the idea of a substance itself. Evidence, so far, has shown that students of the upper primary school (ages 11/12) can understand the idea of a substance to a satisfactory degree, on the basis of simple particle ideas (Johnson and Papageorgiou 2010; Papageorgiou and Johnson 2005). Although this does not necessarily mean that all pupils can provide us with satisfactory explanations for chemical changes, it is important that there is evidence showing that a number of students, who developed particle ideas to a high level, could also satisfactorily explain chemical changes (Papageorgiou et al. 2010). As a result, a number of questions arise: Taking into account that with the help of appropriate teaching methods, young students of those ages (11/12) are probably able to satisfactorily explain chemical changes to a certain degree in terms of the 1st level, is it worth trying to develop such methods for this level? Could such a policy help young students to understand in a simple way some basic concepts that are associated with the chemical changes in order to be able later on (e.g., in the context of the 2nd level of explanations) to understand more sophisticated aspects of them? Could this strategy progressively solve or create problems of misconceptions concerning chemical changes? Is it preferable to defer dealing with explanations of chemical changes to the 2nd level, when students would be able to understand more about the submicroscopic structure of substances?

Some Thoughts Concerning a Possible Introduction of the 1st Level of Chemical Changes Explanations to Young Students

Apparently, it is quite difficult to get particular answers to questions like the above. However, speaking always from the science education researchers' perspective, some thoughts concerning the usefulness of the introduction of the 1st level of chemical changes explanations to young students, along with some deriving difficulties, could be the following:

First of all, the introduction of such explanations to young students in the context of the 1st level provides them time and opportunities to acquire more experience during the educational period. This is of great importance, since, in chemical changes, each case is a specific one with its own characteristics. This is not the case of physical phenomena, where we can involve a number of substances in the same phenomenon under the same conditions. For example, when we study "boiling," we can build a particular explanation no matter if it is about the boiling of water or the boiling of alcohol or the boiling of wax. On the contrary, when we study "burning," then the burning of alcohol is a completely different phenomenon compared to the burning of wax (it needs a completely different handling) or different compared to the burning of a metal. The chemical phenomena can be in general categorized and studied much more difficultly compared to the physical ones. So, the more experience gained, the better the understanding of chemical changes that can be achieved.

Of course, it should be acknowledged that young students can develop alternative ideas, mainly due to the emphasis at the 1st level on different explanations of the idea of the "atom." As Taber (2003, p. 57) reported, such an emphasis can lead to results such as: *molecules are seen as combinations of atoms (e.g., "a group of atoms bonded (joined) together"), and ions are considered to be altered atoms (e.g., "an atom that has lost or gained electrons"), rather than being viewed as entities as fundamental as atoms*. For this reason, the above-reported key premises are introduced, where, for instance, a careful manipulation of the concept of the "molecule" using the introduction of the idea of the bond and its distinction from the intermolecular forces could lead to its conceptualization as a new fundamental entity. However, the risk of the development of alternative ideas by the students is always present, independently of the level of explanations or the age of the students. For example, an inappropriate teaching approach in the context of the 2nd level of explanations (along with other factors) could lead to also other students' misconceptions about the concept of the "molecule." Summarizing such misconceptions, Taber (1997) constructed a model (a "molecular framework" according to Taber), where students commonly believe that there are two types of interactions in an ionic lattice: interactions *within* an ion pair and interactions *between* ion pairs. Thus, although the term "molecule" could not be used by the students, their idea of "ion pairs" implies the existence of molecules in an ionic lattice. Further research on this alternative "molecular framework" in three countries

(Taber 1997; Taber et al. 2012) suggests that the teaching approach and, in general, the whole curriculum context can have an impact on the relevant students' misconceptions.

Besides, although working on the context of the 1st level, alternative ideas can be developed and become obstacles at the next (2nd) level, the same holds true also for the transition between the 2nd and the 3rd levels. Thus, Tsaparlis and Papaphotis (2009) have shown that there are significant problems with the understanding and the use of the probabilistic quantum model by high school students due to their stable prior particle ideas (within the context of the 2nd level). Generally, the effect of developing stable prior ideas within a particular context of work would possibly have consequences on the next one. As a result, the flexibility of the ideas that are developed in the context of a particular level of explanations can determine the possibility to avoid contradictions with more sophisticated ideas that would be developed in the next level. The latter is directly related to the design of the whole context of work in a particular level, and that is why the exact features of the design of the 1st level of explanations is of great importance (along with the teaching methods as well). As Wiser and Smith (2008, p. 230) support, "*at each stage* [of a well designed curriculum]*, new information can be assimilated into students' existing framework to further their knowledge in a way suitable for tackling the next part of the curriculum*." Accordingly, it is very important for the features of the design of this 1st level to have the flexibility to anticipate new entities that will enter later on in higher levels.

For example, since the concept of a "particle" has been introduced properly in association with the basic idea of a "substance," a student could possibly further accept that apart from the atom and the molecule (which explicitly could be discussed in the 1st level of explanations), also other kinds of particle could exist. Thus, it would not be very hard for him/her to work then with "ions" and to broaden other relevant ideas, like that one of giant structure involving also ions. Similarly, since the idea of the "bond" in this design originates from the general idea of "the existence of holdings between particles," a student could be able to further specify this idea when the kinds of bonds (covalent, ionic, or metallic) would be the case. Thus, these kinds could be established in connection to the corresponding kinds of particles that are involved in each case, i.e., molecules, ions, or atoms, respectively. In other words, it is important for this design to pay attention to the introduction of the general, basic ideas, establishing a discipline that can provide coherence in the entrance and the management of new concepts and ideas.

Consequently, the focus of a possible introduction at this 1st level of explanations to young students should be on its design rather than on the age of the students. Since the topic of chemical changes is an important one in science education, maybe it is rather preferable to work for its progressive introduction through the 1st level as opposed to avoiding it until it is possible to work within the most correct scientific level. In fact, the success of this 1st level of explanation depends mainly on the design of the whole context of working and the teaching methods as well. As Wiser and Smith (2008) suggest, we should neither underestimate the capacity of young students to work with simple particle models nor overestimate at the same time the extent to which students' model-building efforts match to those of scientists. According to them, "intermediate models" that students build during their learning progression have their own value. Thus, curricula that help young students through simply designed particle models to develop their own framework for explanations of chemical phenomena could also have their own importance, respectively.

As a result, although one could be skeptical to a certain degree, it might be worth trying to explain chemical changes within the simplicity of the 1st level of explanations at young ages. What we need is, on the one hand, a carefully designed curriculum that takes into account all the above and, on the other, the development of appropriate teaching methods for its better implementation.

References

Andersson, B. (1986). Pupils' explanations of some aspects of chemical reactions. *Science Education, 70*(5), 549–563.

Berland, L. K., & Reiser, B. J. (2009). Making sense of argumentation and explanation. *Science Education, 93*, 26–55.

Chandrasegaran, A. L., & Treagust, D. F. (2008). An evaluation of a teaching intervention to promote students; ability to use multiple levels of representation when describing and explaining chemical reactions. *Research in Science Education, 38*, 237–248.

Cokelez, A., Dumon, A., & Taber, K. S. (2008). Upper secondary French students' chemical transformations and the "Register of models": A cross-sectional study. *International Journal of Science Education, 30*(6), 807–836.

Department for Education and Skills (DfES). (2003). *National strategy: Strengthening the teaching and learning of particles in Key stage 3 science*. London: Crown copyright.

Franco, A. G., & Taber, K. S. (2009). Secondary students' thinking about familiar phenomena: Learners' explanations from a curriculum context where 'particles' is a key idea for organising teaching and learning. *International Journal of Science Education, 31*(14), 1917–1952.

Greek Pedagogical Institute. (2003). *National program of study for primary and secondary education: Science*. Athens: Greek Pedagogical Institute.

Hatzinikita, V., Koulaidis, V., & Hatzinikitas, A. (2005). Modeling pupils' understanding and explanations concerning changes in matter. *Research in Science Education, 35*, 471–495.

Johnson, P. M. (2002). Children's Understanding of substances, part 2: Explaining chemical change. *International Journal of Science Education, 24*(10), 1037–1054.

Johnson, P. M., & Papageorgiou, G. (2010). Rethinking the introduction of particle theory: A substance-based framework". *Journal of Research in Science Teaching, 47*(2), 130–150.

Johnstone, A. H. (2000). Teaching of chemistry – Logical or psychological. *Chemistry Education Research and Practice, 1*(1), 9–15.

Papageorgiou, G., & Johnson, P. M. (2005). Do particle ideas help or hinder pupils' understanding of phenomena? *International Journal of Science Education, 27*(11), 1299–1317.

Papageorgiou, G., Grammatikopoulou, M., & Johnson, P. (2010). Should we teach primary pupils about chemical change? *International Journal of Science Education, 32*(12), 1647–1664.

Taber, K. S. (1997). Student understanding of ionic bonding: Molecular versus electrostatic framework? *School Science Review, 78*, 85–95.

Taber, K. S. (2001). Building the structural concepts of chemistry: Some considerations from educational research. *Chemistry Education Research and Practice, 2*(2), 123–158.

Taber, K. S. (2003). The atom in the chemistry curriculum: Fundamental concept, teaching model or epistemological obstacle? *Foundations of Chemistry, 5*, 43–84.

Taber, K. S., & Watts, M. (2000). Learners' explanations for chemical phenomena. *Chemistry Education Research and Practice, 1*(3), 329–353.
Taber, K. S., Tsaparlis, G., & Nakiboğlu, C. (2012). Student conceptions of ionic bonding: Patterns of thinking across three European contexts. *International Journal of Science Education, 34*(18), 2843–2873.
Tsaparlis, G., & Papaphotis, G. (2009). High-school students' conceptual difficulties and attempts at conceptual change: The case of basic quantum chemical concepts. *International Journal of Science Education, 31*(7), 895–930.
Wiser, M., & Smith, C. L. (2008). Learning and teaching about matter in grades K-8: When should the atomic-molecular theory be introduced? In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 205–239). New York: Routledge.

How Do Students Reason About Chemical Substances and Reactions?

Vicente Talanquer

Introduction

One of the central learning goals in chemistry teaching is to help students understand the relationship between the macroscopic properties of substances and their chemical composition and structure at the submicroscopic level (AAAS 1993; NRC 1996). In particular, we would like students to meaningfully understand how to use atomic–molecular models of matter to explain and predict the properties and behavior of relevant materials in their surroundings. Unfortunately, educational research in the last 40 years has shown that developing such an understanding is not an easy task (Gilbert et al. 2002; Kind 2004; Nakhleh 1992; Taber 2002). Many students struggle to make sense of the various particulate models of matter discussed in their chemistry classes, as well as to properly use them to explain and predict phenomena.

Many of the difficulties that students face in understanding structure–property relationships are described in the now-extensive research literature on alternative conceptions (Duit 2007). This body of work reveals how students' intuitive ideas influence their reasoning in a variety of chemistry topics, from atomic structure to chemical equilibrium. Results from this research are often presented as a list of naïve ideas that students express about different chemistry concepts. Although this approach allows us to identify explicit conceptions that we may want to diagnose and target in our teaching, this "taxonomic" description has been criticized on various grounds. Several authors have suggested, for example, that many of these alternative ideas are not necessarily stable conceptions in students' minds but rather dynamic cognitive constructs created on the spot as pupils are asked to explain or predict phenomena (Brown and Hammer 2008). From this perspective, paying

V. Talanquer (✉)
Department of Chemistry and Biochemistry, University of Arizona,
Tucson, AZ 85721, USA
e-mail: vicente@email.arizona.edu

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_16,

attention to the underlying cognitive elements that constrain student reasoning may be a more productive approach to understanding and predicting student thinking in chemistry (Taber and García-Franco 2010; Talanquer 2006, 2009).

Based on these ideas, in recent years, we have proposed that many of the alternative conceptions expressed by chemistry students seem to be guided and constrained by common underlying presuppositions (implicit assumptions) about the nature of entities and phenomena in our world, as well as by the application of shortcut reasoning procedures (heuristics) that facilitate decision-making under conditions of limited time and knowledge (Talanquer 2006). This way of conceptualizing student reasoning has several pedagogical advantages. First, it helps us make sense of and bring coherence to a variety of reported alternative conceptions and common student errors in different chemistry topics. Moreover, it facilitates making predictions about students' ideas and difficulties in many areas. Finally, it provides a framework for analyzing progression of understanding with training in the discipline (Talanquer 2009). The central goal of this chapter is to illustrate how the proposed approach can be used to analyze student reasoning about the properties of chemical substances and reactions based on atomic–molecular models of matter.

Student Reasoning

Research on student reasoning in the sciences has been closely related to investigations on conceptual change. Work in this area is frequently framed within one of three major theoretical perspectives frequently referred to as the "framework theories" approach (Vosniadou et al. 2008), the "knowledge-in-pieces" standpoint (diSessa 1993), and the "ontological categories" stance (Chi 2008). Thus, to better understand our approach to the analysis of student reasoning in chemistry, it is important to discuss the core ideas behind each of these theoretical viewpoints.

Within the framework theories perspective, student reasoning is assumed to be guided by a network of interrelated knowledge and beliefs about the natural world, such as the idea that physical objects move in continuous paths, which constrain the types of mental models and explanations that people might construct. At the heart of this theoretical approach is the proposition that initial explanations of the natural world are not fragmented ideas but rather form a coherent system of observations, beliefs, and presuppositions, a so-called framework theory (Vosniadou et al. 2008). From the knowledge-in-pieces viewpoint, intuitive knowledge about the world is seen as more fragmented, including a large and diverse collection of phenomenological ideas commonly referred as p-prims (phenomenological primitives); examples of p-prims include notions such as "the closer the source, the stronger its effect." These cognitive elements work by being "activated" by specific circumstances, which may explain the contextuality observed in students' answers to questions asked in slightly different ways (diSessa and Sherin 1998). In the ontological categories approach, human reasoning is assumed to be strongly influenced by the implicit or explicit categories in which people mentally place the different components of the systems of interest. For example, we can safely assume that solid objects will persist in time and space, that is, they will move in continuous paths and they will not spontaneously change shape or decrease in size. If an object does not behave in such a way, then we would not think of it as a solid object (Chi 2008).

Although the research literature on conceptual change sometimes portrays the above theoretical perspectives as competing research paradigms, the analysis of recent work within each of these research camps reveals points of agreement on several key issues. However, it also highlights the challenges that we face in characterizing students' knowledge as coherent versus fragmented, as stable versus dynamic, or as consistent across tasks versus highly contextualized. Rather than taking a particular stance in the conceptual change debate, the goal of our work has been to generate a framework in which elements from different perspectives in the field are used to build an explanatory and predictive approach to the analysis of students' ideas about fundamental chemistry concepts. The central goal is to create interpretative tools that can help teachers make sense of a wide range of alternative ideas that students may express as they learn chemistry. To illustrate our core ideas, let us describe what may happen in our students' minds as they confront a task that requires the analysis of some entity or phenomenon.

Research in cognitive and developmental psychology suggests that when people interact with an object or event, prior knowledge, perceptual information, and language cues are used by the mind to build a mental representation for recognition and categorization purposes (Baillargeon et al. 2009; Gelman 2009). Once a mental representation is created, associative thinking, analogical reasoning, and metaphorical linking help us classify the entity or phenomenon as belonging to a certain category within or across knowledge domains (Bowdle and Gentner 2005; Vosniadou and Ortony 1989). For example, we may recognize a rock as a "solid object" because it feels rigid and heavy. Our categorizations of entities and phenomena have crucial repercussions on how we reason with and about them (Chi 2008). This is mainly because people implicitly assume that the properties of entities and phenomena are determined by the underlying properties that define the category to which they belong. Categories capture causal patterns and guide and constrain our reasoning about what is possible.

Let us imagine that we ask a young child to justify or explain the presence of tiny droplets of water on the external surface of a glass full with water just taken out of the refrigerator. Based on prior experiences, it is likely that he or she will think of the phenomenon as a "causal" process, that is, he or she will assume the existence of an active agent responsible for the event (Andersson 1986). Now, depending on the context, his or her prior knowledge, as well as perceptual and language cues, the child may decide that this is a "transfer" event and propose, for example, that someone with wet hands touched the glass. However, in the process of building the explanation, the child may remember seeing water filtering through paper or ceramic vases. Thus, he or she may choose to suddenly look at the phenomenon as a "passing-through" event in which water from the inside passed through the glass.

The assumptions that people make about the properties and behaviors of the members of a given category act as cognitive constraints that guide and support, but also constrict, their reasoning. These cognitive constraints help us make decisions about what behaviors are possible or not and about what variables are most relevant in determining behavior. They also support the development or application of decision rules and heuristics to make predictions about how the object will behave when involved in different processes or events. These cognitive elements give rise to dynamic but constrained knowledge systems whose goal is not necessarily to achieve global conceptual coherence, but rather local explanatory coherence and efficient inference and decision-making as we work through a specific task in a determined context (Brown and Hammer 2008; Sloman 1996). Cognitive constraints do not provide fully mechanistic models of entities and phenomena, but help us recognize relevant properties and sense relational patterns. They allow us to make reasonable, adaptive inferences about the world given limited time and knowledge. They often generate acceptable answers with little effort, but sometimes lead to severe and systematic biases and errors (Hatano and Inagaki 2000; Keil 1990).

A variety of researchers in cognitive science, developmental psychology, and science education have identified diverse implicit cognitive elements that seem to guide and support, but also constrain, students' reasoning in different domains. They have referred to them in different ways, such as core knowledge (Spelke and Kinzler 2007), implicit presuppositions (Vosniadou 1994), ontological beliefs (Chi 2008), phenomenological primitives (diSessa 1993), intuitive rules (Stavy and Tirosh 2000), fast and frugal heuristics (Todd and Gigerenzer 2000), and conceptual resources (Redish 2004). As can be seen in this list, major proponents of the three dominant theoretical perspectives in conceptual change discussed at the beginning of this section (Chi 2008; diSessa 1993; Vosniadou 1994) highlight the existence of cognitive elements that, once activated, act as constraints on further reasoning. However, there is considerable debate on the extent to which these types of implicit cognitive elements form coherent integrated knowledge systems or more fragmented collections of cognitive biases (Brown and Hammer 2008; Vosniadou et al. 2008). It is likely that their level of integration may vary depending on the nature of the knowledge domain and the prior knowledge and experiences of each individual.

Our approach to the analysis of student reasoning in chemistry has been that, beyond issues of coherence, stability, and contextuality of students' ideas about the world, we need to better understand the nature of the cognitive elements that guide and constrain student thinking. Our analysis of the research literature on students' alternative conceptions in chemistry, together with the results of our own research studies, suggest that these cognitive constraints seem to fall into two major groups (Talanquer 2006):

- *Tacit presuppositions* about the properties and behavior of the entities and phenomena in the domain (*implicit assumptions*)
- *Reasoning strategies* to make judgments and decisions under conditions of uncertainty (*heuristics*)

The extent to which these cognitive elements form an integrated and comprehensive knowledge system may vary from student to student. However, our claim is that tacit categorization decisions about the nature of chemical entities and phenomena involved in a given problem trigger implicit knowledge and reasoning strategies that act as constraints on further reasoning. Thus, a major goal of our research work has been to characterize the most common and overarching constraints that seem to guide naïve learners' reasoning about chemical entities and phenomena. In the following sections, we present examples of our approach and discuss what our results reveal about changes in student reasoning with training in the discipline.

Implicit Assumptions

The categorization on an entity or phenomenon as belonging to a certain class triggers implicit assumptions about its properties and behavior. For example, if we think of an atom as a rigid solid ball, we will expect it to be impenetrable and to move in continuous trajectories; we will assume that many of its properties, such as mass, volume, or color, will persist over time and space. Thus, paying close attention to the implicit or explicit categorization decisions made by students about the nature of chemical substance and processes can provide invaluable information about the underlying assumptions that guide their thinking. To illustrate this idea, in this section, we discuss two examples of overarching assumptions about the nature of chemical substances and reactions that seem to constrain the reasoning of a large fraction of chemistry students.

Research on secondary school and college students' ideas about the properties of atoms and molecules indicates that many students tend to assign similar properties to the submicroscopic components of a substance as to a macroscopic sample of the material. Thus, if the substance is red, its particles are assumed to have the same color; if the material expands when heated, its atoms or molecules should do the same (Kind 2004; Nakhleh 1992; Taber and García-Franco 2010). In our research, we have described this way of thinking as relying on an "inheritance assumption," in which a person implicitly presupposes that substances inherit their properties from those of the individual submicroscopic components (Talanquer 2006, 2009). One may hypothesize that this assumption results from conceiving chemical substances as simple, in the case of chemical elements, or composite, when thinking about chemical compounds, aggregates, or clusters of atoms with relatively fixed properties. If this is the case, the properties of a macroscopic sample of a given substance are likely to be conceived as resulting from the weighted average of the properties attributed to the distinct types of particles present in the system (additive thinking).

To test this hypothesis, we have conducted several studies in which we have asked students to make predictions about the properties of chemical compounds based on information about the macroscopic properties of the chemical elements that react to form such compounds (Talanquer 2008). Figure 1 illustrates prototypical results for students entering their first general chemistry course at the college level (GC1), students that finished such a course (GC2), and students entering a graduate program in chemistry (GS). The figure includes results for students' predictions about the (a) color and (b) state of matter of the chemical product of the reaction between generic

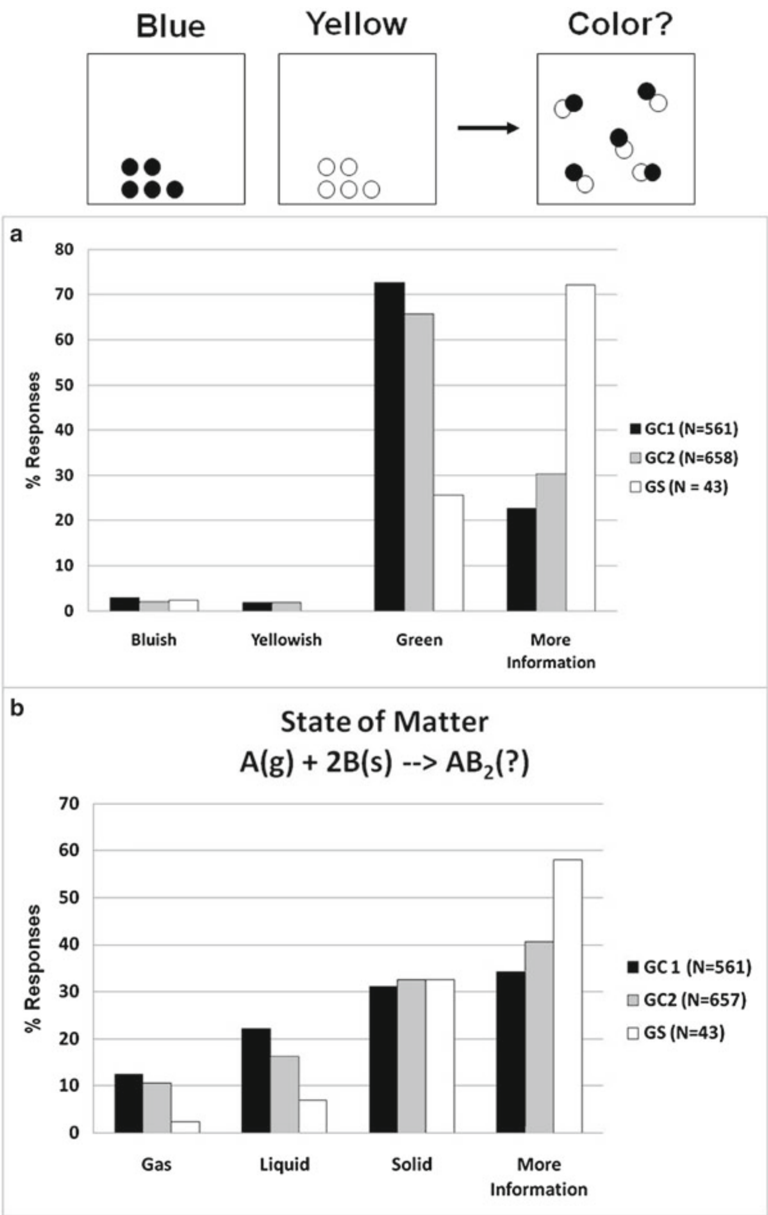


Fig. 1 Predictions of different groups of chemistry students for (**a**) the color and (**b**) the state of matter of the product of the chemical reaction of chemical substances with known properties. *GC1* first semester of general chemistry, *GC2* second semester of general chemistry, *GS* graduate students

chemical elements depicted using either particulate or symbolic representations. In each case, students were asked to select the most likely properties of the product or to indicate whether more information was needed to make the prediction.

As shown in Fig. 1, a significant proportion of students entering a general chemistry course at the college level (GC1) seem to think of chemical compounds as composite aggregates with properties determined by the weighted average of the intrinsic properties of its constituent particles. Thus, for example, they predict the color of the product of a one-to-one reaction between a yellow substance and a blue substance to be green (Fig. 1a), and they consider that the product of a one-to-two reaction between a gaseous and a solid substance, respectively, is more likely to be solid than gas (Fig. 1b). We have observed the same type of reasoning in students' predictions of a variety of physical and chemical properties, such as smell, taste, malleability, electrical conductivity, and chemical reactivity of the product. In general, over two thirds of this population of students commonly selects answers that indicate that they apply additive thinking to make their predictions.

Figure 1 also illustrates the little impact that a single general chemistry course has on students' implicit assumptions about the nature of chemical elements and compounds. Although in general there is a smaller proportion of GC2 students who seem to rely on additive thinking to make their predictions, the differences in GC1and GC2 students' responses to these types of questions are consistently nonsignificant. Major differences are more commonly detected when comparing student populations with markedly different years of training in the discipline, such as the entering college students (GC1) and entering graduate students (GS) in Fig. 1. These results suggest that conceptualizing physical and chemical properties as emerging from the interactions of the many components in a given system rather than as a simple combination of the intrinsic properties of such components is a rather difficult task for most students.

The analysis of students' alternative conceptions about physical and chemical processes suggests that chemistry students also seem to hold strong implicit assumptions about the nature of these types of events (Andersson 1986; Kind 2004; Taber 2002; Taber and García-Franco 2010; Talanquer 2006, 2010). Some of these presuppositions seem to stem from a conceptualization of chemical reactions as processes that are driven by (a) leading agents acting upon or within a system or by (b) intentional agents with well-defined purposes. In general, we may expect students to think of chemical reactions as driven by active agents when they recognize the presence of a potential initiator (e.g., spark, match) or they identify some atoms or molecules as more reactive within a system (e.g., higher electronegativity, more polar). On the other hand, claims of purposeful or intentional behavior are more likely to be made when the presence of a leading or enabling agent is not obvious and some states of a system are assumed to be more desirable than others. In these cases, students may consider that atoms or molecules react in order to attain a more stable final state (e.g., full valence shell, lower energy) or reinstate equilibrium.

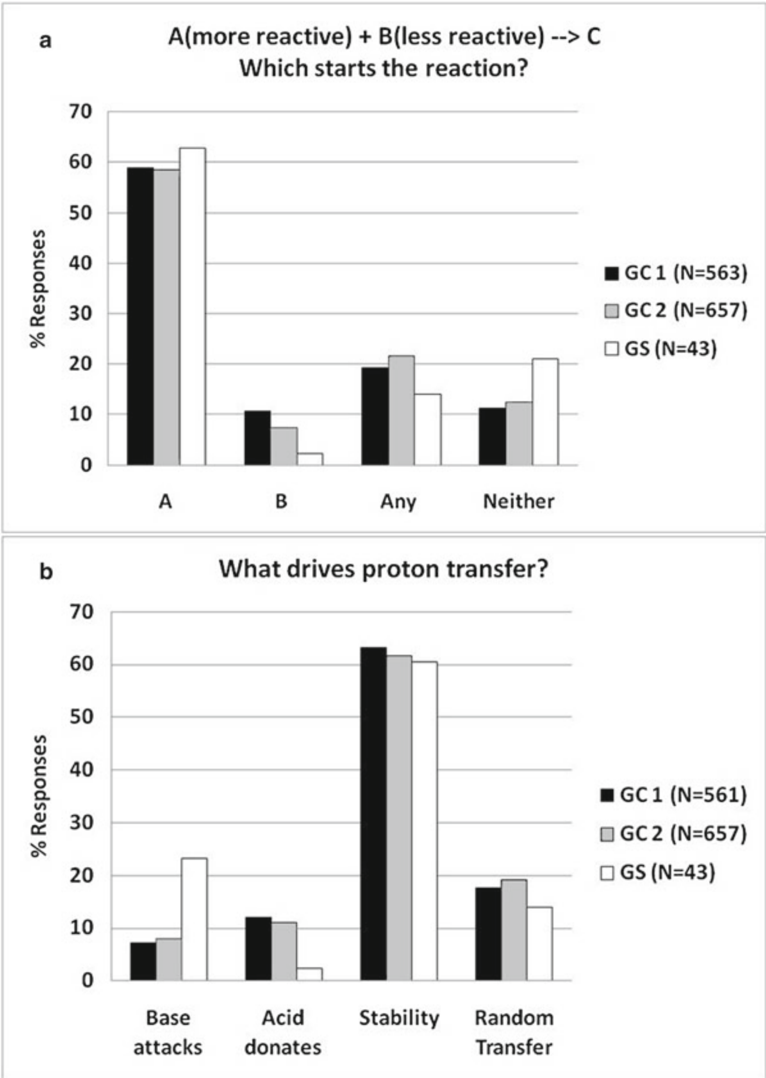


Fig. 2 Predictions of different groups of chemistry students for (**a**) the leading agent in a chemical reaction between a more reactive (A) and a less reactive (B) species and (**b**) the underlying reason why acids and bases react via proton transfer. *GC1* first semester of general chemistry, *GC2* second semester of general chemistry, *GS* graduate students

We have explored students' assumptions about "centralized causality" (active or enabling agents) and "teleology" (intentional agents) in chemical reactions using questionnaires and individual interviews. Figure 2 includes prototypical distributions of answers for two representative questions posed to students with different levels of training in chemistry. In the question associated with Fig. 2a, students were told that compound A (more reactive) reacted with compound B (less reactive) to form compound C and then asked to decide which species could be identified as the most likely starter of the process (A, B, any of them, neither of them). As shown in this figure, close to 60 % of the students in each of the groups, regardless of level of training, indicated that the molecules of the more reactive compound would initiate the reaction by acting on molecules of the less reactive substance. On the other hand, results depicted in Fig. 2b correspond to a question that asked students to judge which of the following phenomena was most likely responsible for proton transfer between an acid and a base: (a) the molecules of the base attack the molecules of the acid and take the protons away; (b) the molecules of the acid spontaneously donate protons to molecules of the base; (c) hydrogen ions are transferred between molecules so that the two types of species become more stable; and (d) hydrogen ions randomly move between molecules of the acid and the base but the energy cost of this transfer is not the same in both directions. In this case, close to 60 % of the students in each of the groups selected the answer that implied intentional behavior to attain stability.

Quite surprisingly, our results suggest that assumptions of centralized causality or teleology in the behavior of reacting atoms and molecules do not subside with training in the discipline. In fact, in some cases they seem to become more prevalent. One may speculate that this particular result may be linked to frequent student exposure to conventional mechanistic representations in chemistry that depict electron-rich species as acting on electron-deficient species. Based on our results, it is difficult to ascertain the extent to which chemistry students at the different educational levels actually attribute intentional behaviors to atoms or molecules. Our analysis of general chemistry textbooks reveals that our own educational resources and ways of teaching may foster this type of thinking (Talanquer 2007). However, results from our studies clearly indicate that a large proportion of students tend to judge teleological statements as truthful explanations of chemical reactivity. Similarly, many students exhibit a clear preference for teleological justifications of chemical change versus explanations that describe chemical reactivity as the result of energetically or entropically biased random processes (emergent processes).

Heuristics

Implicit assumptions about the nature of chemical entities and phenomena help students make predictions about their properties. These presuppositions help students identify variables or cues that may be relevant in any given context. However, chemical substances and processes tend to be multivariate complex systems, and making proper judgments and decisions about their behavior frequently requires careful identification of and discrimination among many variables. For example, in deciding whether sodium chloride (NaCl) can be expected to have a higher melting point than sodium bromide (NaBr), we need first to recognize that these two substances can be modeled as ionic compounds. Then, we should acknowledge that their physical properties will be largely determined by the charge and size of the ions present in the system. Next, we should remember or find a way to infer the actual ion charge and size values, and, finally, we should be able to integrate all of this information to make a decision. Research on student reasoning when facing these types of problems indicates that many chemistry students do not apply this analytical way of reasoning, but rather rely on shortcut reasoning strategies (heuristics) to make their decisions (Maeyer and Talanquer 2010; McClary and Talanquer 2011).

Heuristic reasoning in judgment and decision-making has been analyzed from a variety of research perspectives (Sloman 1996; Todd and Gigerenzer 2000; Evans 2006; Stavy and Tirosh 2000). Despite differences in conceptualization and approach (Evans 2008), existing frameworks highlight the capacity of the human mind to make decisions with very little time and information, using implicit and preconscious reasoning mechanisms. These types of reasoning strategies have been characterized as fast and frugal because they employ a minimum amount of time and information to generate a choice or decision and adaptive or ecologically rational because they fit to the structure of the environment in which they are used (Todd and Gigerenzer 2000). Heuristic processing can be expected to dominate over more analytical ways of thinking when a person has less knowledge, capacity, or motivation to do well in a task. Although heuristics usually provide satisfactory answers, they do not always lead to the correct solution and seem to be responsible for many systematic biases and errors in human reasoning.

Most of the research on heuristic reasoning has been completed in nonacademic contexts. However, there is clear evidence that this mode of thinking is also commonly used by students in science and mathematics classrooms (Stavy and Tirosh 2000; Leron and Hazzan 2006). In the particular case of chemistry, the application of heuristic reasoning has been reported by different authors. For example, Taber and Bricheno (2009) have described the different types of heuristics used by secondary school students when completing chemical word equations. Our own research has revealed the prevalent use of heuristic reasoning by college chemistry students when asked to compare diverse physical and chemical properties of chemical compounds based on information about their composition and structure (Maeyer and Talanquer 2010; McClary and Talanquer 2011). In the following paragraphs, we summarize major results emerging from these latter types of studies that provide insights into how chemistry students make decisions about the properties of chemical substances.

Our investigations of student heuristic reasoning in chemistry have relied on tasks that ask college students enrolled in general or organic chemistry classes to rank sets of three or four chemical substances based on the relative value of physical (e.g., boiling point, melting point) or chemical (e.g., acidity, basicity) properties. Research data have been collected in the form of both short questionnaire responses and individual interviews. The results of our studies suggest that a large proportion of chemistry students rely on heuristic strategies, rather than analytical thinking based on atomic–molecular models of matter, to make ranking decisions. Heuristic reasoning allowed participants in our studies to reduce cognitive effort by minimizing the number of cues that they needed to evaluate to make a decision, facilitating the recall of cue values, or simplifying the evaluation of cue effects. Unfortunately, this way of reasoning often led students astray. Among the major shortcut reasoning strategies used by chemistry students to make ranking decisions, we may highlight the following:

- *Recognition*: When using this heuristic, a decision is made by selecting an object in a set based on the extent to which the object is recognized and is known to exhibit the property under comparison (Goldstein and Gigerenzer 2002). For example, many students may select NaCl as the most water-soluble substance in a set that also included NaBr and NaI simply because they recognize sodium chloride as common soluble substance.
- *Representativeness*: In this case, the decision is made assuming commonalities in properties and behaviors between objects with similar appearance (Gilovich et al. 2002). For example, in making decisions about relative acid strength, students may rely on the presence of certain functional groups, such as the carboxylic (–COOH) and the hydroxyl (–OH) groups, to judge the representativeness of a substance as a strong acid or a strong base.
- *One-reason decision-making*: When using this type of heuristic, the decision is based on the search for a single differentiating cue that can be used to choose between given options (Todd and Gigerenzer 2000). In general, the final decision is based on selecting the option with the higher cue value on the choice criterion. In this sense, once a differentiating cue is identified, the decision is typically made using a "more A–more B" type of intuitive rule (Stavy and Tirosh 2000). For example, in choosing which compound, MgO or BaO, has a higher melting point, a student may stop the search for relevant cues once he or she realizes that Ba is heavier than Mg, thus using "weight" to make the decision. The choice of weight as a differentiating characteristic could be informed by implicit assumptions about the factors that determine how difficult it is to melt a solid. This student is then likely to select BaO as the compound with the highest melting point using a "more weight–higher melting point" type of intuitive rule.

Given that heuristics tend to be task-specific reasoning strategies, one can expect that the application of specific heuristics will depend on specific task features. Thus, which type of heuristic is used will be strongly influenced by the particular content and structure of the problem at hand. For example, in our studies, the use of the *recognition* heuristic was commonly triggered by questions that included common substances, such as NaCl, with known high values in the ranking criterion (e.g., solubility). On the other hand, tasks in which differences in atomic composition were the salient differentiating features between substances tended to favor the application of a one-reason decision-making heuristic based on the identification of differences in implicit atomic properties (e.g., electronegativity, atomic mass, or size). Although this latter approach may be certainly useful in generating the correct answers, our results indicate that many students struggle to identify relevant factors, misapply them, or overgeneralize their range of application. One-reason decision-making was also frequently applied when differences between substances were due to implicit structural or electronic factors. However, in this case, students frequently considered surface features of chemical representations, such as number of atoms or bonds of certain type represented in the different molecular drawings, to make their decisions (McClary and Talanquer 2011).

Conclusions and Implications

The central goal of this work has been to illustrate how the analysis of chemistry student thinking based on the identification of implicit assumptions about the nature of chemical substances and reactions, together with the elicitation of shortcut reasoning strategies used to make decisions, can help us better explain and predict the difficulties that our students face when asked to use atomic–molecular models of matter to analyze structure–property relationships. This analytical framework is also useful for revealing ways of thinking that are resistant to change with training in the discipline. Ultimately, the proposed approach to the analysis of student reasoning in chemistry highlights the need to go beyond the simple identification of specific alternative conceptions in different topics to look for underlying patterns in student thinking that need to be uncovered and critically analyzed in the chemistry classroom.

Although for purposes of description we found convenient to present examples of implicit assumptions and reasoning heuristics separately, it is important to recognize that these cognitive constraints often operate in conjunction with each other. For example, in trying to explain boiling point elevation in aqueous solutions, students often apply a "centralized causality" assumption (i.e., there is a leading causal agent) and rely on heuristics such as covariance or proximity to look for a probable cause (Talanquer 2006). Thus, many of them incorrectly consider that the phenomenon is due to the attractive forces exerted by solute particles on nearby water molecules (Talanquer 2010). Implicit assumptions about the nature of objects and events, either at the macroscopic or submicroscopic levels, guide students' search and selection of relevant cues in making decisions or building explanations. In fact, in many cases, the use of certain heuristic will be triggered by implicit assumptions about the nature of the system of interest. For example, in predicting the color or state of matter of the products for the chemical reactions depicted in Fig. 1a and b, respectively, an inheritance assumption justifies the use of the weighted average of the properties of the elemental components (additive heuristic) to make the prediction.

Given a certain task, different students can be expected to rely on implicit assumptions and heuristic reasoning in distinct ways. Prior knowledge and level of understanding will affect students' ideas about what factors are relevant and how their effects should be weighed. The less knowledge of a topic and the less familiarity with a certain task, the higher the likelihood that students will rely on both domain-general heuristics and naïve implicit assumptions to make decisions, build explanations, or provide justifications. The larger and more integrated the knowledge base, and the more experience solving certain types of tasks, the more likely for people to make the correct assumptions and to apply either analytical reasoning or appropriate domain-specific heuristics in solving these problems.

It should be noted that expert chemists actually rely on a variety of heuristic rules based on the association of pairs of variables to make plausible predictions; these associative rules link the structural features of substances to their physical and chemical properties. For example, the more polar or polarizable molecules are, the higher the boiling and melting points of the substance; the larger the ion charge in an ionic compound, the higher its expected melting point. What our studies have revealed is that although students also tend to use associative rules as a basic strategy to make predictions about the properties of chemical substances, they often either build wrong associations or use them incorrectly (Maeyer and Talanquer 2010; McClary and Talanquer 2011). It is also common for students to discount the effect of multiple variables when building explanations or making predictions in different types of tasks. If they identify the potential effect of more than one variable, they tend to treat them independently and additively, rather than integrating several factors in a problem into a coherent whole, as experts often do.

The identification of the tacit cognitive constraints that guide but also constrict students' thinking at different educational levels may not be an easy task. These are preconscious cognitive elements that need to be inferred from the careful and critical analysis of students' decisions, explanations, and predictions while working on different tasks. Fortunately, we can rely on results from research in areas such as child development (Baillargeon et al. 2009; Spelke and Kinzler 2007), human reasoning (Gilovich et al 2002; Todd and Gigerenzer 2000), and language and thought (Pinker 2007) to guide our analysis. There are also insightful studies in science education that describe common reasoning patterns or strategies used by students when analyzing physical or biological entities that can be relevant in understanding student thinking in chemistry. These studies include investigations on students' ideas about causality (Andersson 1986; Grotzer 2003), dynamic systems (diSessa 1993; Resnick 1994; Viennot 2001), and physical quantities (Reiner et al. 2000).

It is common for educators to state that, contrary to what happens with core concepts and ideas in physics and biology, many of the alternative conceptions expressed by chemistry students originate in the chemistry classroom rather than through their daily interactions with the natural world. The argument is based on the claim that students do not have much prior knowledge or experiences related to many of the abstract entities or processes introduced by chemistry teachers (e.g., atoms, molecules, chemical equilibrium). However, this viewpoint fails to recognize that people strongly rely on analogical and metaphorical reasoning to make sense of abstract concepts and ideas, and, thus, implicit assumptions about the nature of concrete objects and events play a major role on how students interpret anything that the teacher says. For example, it is likely that when a teacher describes a chemical substance as made up of tiny particles, many students infer that a substance may be thought of as a simple aggregate of small pieces of the material. To blame instruction for these types of conceptualizations is an oversimplification of a complex problem, and it is out of step with what we know about how people construct understandings.

One can certainly recognize that some approaches to teaching chemistry may foster the development and entrenchment of certain alternative conceptions. For example, traditional ways of introducing students to concepts about chemical bonding may be responsible for the pervasive use of the "octet rule" as an explanatory framework for chemical stability and reactivity (Taber 1998, 2009). However, I would claim that the pervasiveness and resiliency of this type of thinking is likely associated with students' cognitive bias toward teleological explanations when they fail to recognize leading causal agents or another type of causal mechanism. From this perspective, changing students' ideas in this area will require more than changing how the octet rule is introduced and discussed in the chemistry classroom. It will demand helping students acknowledge the implicit assumptions that they make when building their explanations as well as helping them evaluate the validity of their arguments. It will also require exposing students to alternative ways of thinking, critically analyzing their scope and limitations.

Our studies consistently reveal that a significant fraction of chemistry students at all educational levels do not think of atoms and molecules at the submicroscopic scale or of chemical substances and reactions at the macroscopic level, as dynamic entities whose properties emerge from the dynamic interactions among their components. On the contrary, they treat them as simple or composite static objects with intrinsic powers or intentions. Consequently, many students fail to build or even consider mechanistic explanations based on the analysis of competing random processes involving many subcomponents. To help students in this area, several authors have proposed different types of instructional interventions. For example, Grotzer (2003) has shown the positive effects of involving students in inquiry-learning experiences that draw their attention to different ways of modeling causal relations in a system. Slotta and Chi (2006) have demonstrated that explicitly training students to recognize core attributes of emergent processes can help them gain a deeper understanding of fundamental concepts. Jacobson and Wilensky (2006) have illustrated the power of interactive computer simulations in helping students recognize different emergent levels in the analysis of complex systems.

In general, our results suggest that chemistry education would benefit by a more careful analysis of the underlying assumptions and reasoning heuristics that guide students' thinking in different contexts. This knowledge would aid instructors in designing learning opportunities that can better help students monitor their own reasoning while engaged in specific tasks. This type of work should involve students in collectively analyzing the nature of the most common misleading assumptions, distracting factors, and appealing reasoning heuristics for the less experienced thinkers. Our studies also highlight the need to engage chemistry students at all educational levels in model-building and model-analyzing activities that force them to make their thinking explicit, guide them in the construction of alternative models and arguments, and make them discuss and reflect on their explanatory and predictive power.

References

American Association for the Advancement of Science (AAAS). (1993). *Benchmarks for science literacy*. Washington, DC: Oxford University Press.

Andersson, B. (1986). The experimental gestalt of causation: A common core to pupils' preconceptions in science. *European Journal of Science Education, 8*(2), 155–171.

Baillargeon, R., Li, J., Ng, W., & Yuan, S. (2009). An account of infants' physical reasoning. In A. Woodward & A. Needham (Eds.), *Learning and the infant mind* (pp. 66–116). New York: Oxford University Press.

Bowdle, B., & Gentner, D. (2005). The career of metaphor. *Psychological Review, 112*(1), 193–216.

Brown, D. E., & Hammer, D. (2008). Conceptual change in physics. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 127–154). New York: Routledge.

Chi, M. T. H. (2008). Three kinds of conceptual change: Belief revision, mental model transformation, and ontological shift. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 61–82). New York: Routledge.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*, 165–255.

diSessa, A. A., & Sherin, B. L. (1998). What changes in conceptual change? *International Journal of Science Education, 20*(10), 1155–1191.

Duit, R. (2007). *Bibliography STCSE*: *Students*' *and teachers*' *conceptions and science education*. Kiel: Leibniz Institute for Science Education, IPN. Available at www.ipn.uni-kiel.de/aktuell/stcse/

Evans, J. S. B. T. (2006). The heuristic-analytic theory of reasoning: Extension and evaluation. *Psychonomic Bulletin & Review, 13*(3), 378–395.

Evans, J. S. B. T. (2008). Dual-processing accounts of reasoning, judgment, and social cognition. *Annual Review of Psychology, 59*, 255–278.

Gelman, S. A. (2009). Learning from others: Children's construction of concepts. *Annual Review of Psychology, 60*, 115–140.

Gilbert, J. K., De Jong, O., Justi, R., Treagust, D., & van Driel, J. (Eds.). (2002). *Chemical education: Towards research-based practice*. Dordrecht: Kluwer.

Gilovich, T., Griffin, D., & Kahneman, D. (Eds.). (2002). *Heuristics and biases: The psychology of intuitive judgment*. Cambridge: Cambridge University Press.

Goldstein, D. G., & Gigerenzer, G. (2002). Models of ecological rationality: The recognition heuristic. *Psychological Review, 109*(1), 75–90.

Grotzer, T. A. (2003). Learning to understand the forms of causality implicit in scientifically accepted explanations. *Studies in Science Education, 39*, 1–74.

Hatano, G., & Inagaki, K. (2000). Domain-specific constraints on conceptual development. *International Journal of Behavioral Development, 24*(3), 267–275.

Jacobson, M. J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *The Journal of the Learning Sciences, 15*(1), 11–34.

Keil, F. C. (1990). Constraints on constraints: Surveying the epigenetic landscape. *Cognitive Science, 14*(1), 135–168.

Kind, V. (2004). *Beyond appearances: Students' misconceptions about basic chemical ideas* (2nd ed.). London: Royal Society of Chemistry.

Leron, U., & Hazzan, O. (2006). The rationality debate: Application of cognitive psychology to mathematics education. *Educational Studies in Mathematics, 62*, 105–126.

Maeyer, J., & Talanquer, V. (2010). The role of intuitive heuristics in students' thinking: Ranking chemical substances. *Science Education, 94*, 963–984.

McClary, L., & Talanquer, V. (2011). Heuristic reasoning in chemistry: Making decisions about acid strength. *International Journal of Science Education, 33*(10), 1433–1454.

Nakhleh, M. B. (1992). Why some students don't learn chemistry. *Journal of Chemical Education, 69*(3), 191–196.

National Research Council (NRC). (1996). *National Science Education Standards*. Washington, DC: National Academy Press.
Pinker, S. (2007). *The stuff of thought: Language as a window into human nature*. New York: Penguin.
Redish, E. F. (2004). A theoretical framework for physics education research: Modeling student thinking. In E. F. Redish & M. Vicentini (Eds.), *Proceedings of the international school of physics, "Enrico Fermi" course CLVI*. Amsterdam: Ios Press.
Reiner, M., Slotta, J. D., Chi, M. T. H., & Resnick, L. B. (2000). Naive physics reasoning: A commitments to substance-based conceptions. *Cognition and Instruction, 18*(1), 1–34.
Resnick, M. (1994). *Turtles, termites, and traffic jams: Explorations in massively parallel microworlds*. Cambridge, MA: MIT Press.
Sloman, S. A. (1996). The empirical case for two systems of reasoning. *Psychological Bulletin, 119*(1), 3–22.
Slotta, J. D., & Chi, M. T. H. (2006). Helping students understand the challenging topics in science through ontology training. *Cognition and Instruction, 24*, 261–289.
Spelke, E. S., & Kinzler, K. D. (2007). Core knowledge. *Developmental Science, 10*, 89–96.
Stavy, R., & Tirosh, D. (2000). *How students (mis-)understand science and mathematics: Intuitive rules*. New York: Teachers College Press.
Taber, K. S. (1998). An alternative conceptual framework from chemistry education. *International Journal of Science Education, 20*(5), 597–608.
Taber, K. (2002). *Chemical misconceptions – Prevention, diagnosis and cure. Vol. I: Theoretical background*. London: Royal Society of Chemistry.
Taber, K. (2009). College students' conceptions of chemical stability: The widespread adoption of a heuristic rule out of context and beyond its range of application. *International Journal of Science Education, 31*(10), 1333–1358.
Taber, K. S., & Bricheno, P. A. (2009). Coordinating procedural and conceptual knowledge to make sense of word equations: Understanding the complexity of a 'simple' completion task at the learner's resolution. *International Journal of Science Education, 31*, 2021–2055.
Taber, K. S., & García-Franco, A. (2010). Learning processes in chemistry: Drawing upon cognitive resources to learn about the particulate structure of matter. *The Journal of the Learning Sciences, 19*(1), 99–142.
Talanquer, V. (2006). Common sense chemistry: A model for understanding students' alternative conceptions. *Journal of Chemical Education, 83*(5), 811–816.
Talanquer, V. (2007). Explanations and teleology in chemistry education. *International Journal of Science Education, 29*(7), 853–870.
Talanquer, V. (2008). Students' predictions about the sensory properties of chemical compounds: Additive versus emergent frameworks. *Science Education, 92*(1), 96–114.
Talanquer, V. (2009). On cognitive constraints and learning progressions: The case of structure of matter. *International Journal of Science Education, 31*(15), 2123–2136.
Talanquer, V. (2010). Exploring dominant types of explanations built by general chemistry students. *International Journal of Science Education, 32*(18), 2393–2412.
Todd, P. M., & Gigerenzer, G. (2000). Precis of simple heuristics that make us smart. *The Behavioral and Brain Sciences, 23*, 727–780.
Viennot, L. (2001). *Reasoning in physics: The part of common sense*. Dordrecht: Kluwer.
Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*, 45–69.
Vosniadou, S., & Ortony, A. (Eds.). (1989). *Similarity and analogical reasoning*. New York: Cambridge University Press.
Vosniadou, S., Vamvakoussi, X., & Skopeliti, I. (2008). The framework theory approach to the problem of conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 3–34). New York: Routledge.

Developing Chemical Understanding in the Explanatory Vacuum: Swedish High School Students' Use of an Anthropomorphic Conceptual Framework to Make Sense of Chemical Phenomena

Keith S. Taber and Karina Adbo

Introduction

Introductory chemistry courses in Sweden usually begin by attempting to set up a basic conceptual framework within which to situate chemical phenomena. The intention of such an approach is to familiarise students with the abstract, formal chemical concepts that provide the basis for a chemist's understanding of matter and for the repertoire of explanations that are considered appropriate in chemistry classes. So students learn about particle models of matter and concepts such as chemical reaction and chemical bond, and the octet rule heuristic for identifying stable ions and molecules.

Although change of state is modelled earlier in secondary education in terms of changes in the arrangement of particles, many of the models and laws used for deriving acceptable causal explanations for chemical phenomena are not themselves presented prior to advanced high school courses. By the time students are taught these ideas, they have already been familiar with, and have worked with, the basic concepts over some years (Adbo and Taber 2009). The issue, of how to provide adequate descriptive accounts (e.g. of chemical reactions at the submicroscopic level) without being able to offer causes for why events occur, then becomes a dilemma in introductory chemistry courses. One way that teachers and textbook authors resolve this issue is through the use of metaphors, anthropomorphic language and teleological formulations (Kallery and Psillos 2004; Packiam Alloway and Archibald 2011; Swanson 2011).

K.S. Taber (✉)
Faculty of Education, University of Cambridge, Cambridge, UK
e-mail: kst24@cam.ac.uk

K. Adbo
Department of Chemistry and Biomedical Sciences, Linnæus University, Kalmar, Sweden

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_17,

Animism, Anthropomorphism and Teleology

Originally the term animism was defined by Piaget (1929/1973, p. 194) as ‘the tendency to regard objects as living and endowed with will’. Anthropomorphism is an extension of animism and is the term used when *human* feelings and emotions also are assigned to nonliving things. Teleology is used to describe the special circumstance when anthropomorphism is used in explanations to provide ‘function and purpose’ (Talanquer 2007) as being the cause of an event. For example, if it was said that evolution acts in order to bring about ‘higher’ (more complex) forms of life, then that would be a teleological formulation as it implies evolution has a purpose and is actively working towards a particular type of outcome. In this chapter, we focus on the anthropomorphism in students’ comments in interviews, but some of the comments we report can also be considered to be teleological in nature.

Anthropomorphic Thinking About Atoms

Based on an interview study with 16–19-year-old English college students, Taber (1998) reported a high level of anthropomorphism in student explanations of basic chemical concepts. Taber argued that on entry to college from school science, these students predominantly thought about chemical phenomena at the submicroscopic level in terms of the octet rule as an explanatory principle (see also Taber, “A Common Core to Chemical Conceptions: Learners’ Conceptions of Chemical Stability, Change and Bonding”, this volume). For the students, bonds formed and reactions occurred, so that atoms could achieve full shells or octets of electrons. So student explanations were commonly phrased in terms of what an atom might ‘want’ or ‘need’, and atoms were considered the active entities in reactions, even though very few reactants in chemical reactions are comprised of discrete atoms. This way of thinking was also used in explaining patterns of ionisation energies and leads to students considering quite bizarre species (such as the Na^{7-} anion) as stable.

The Role and Status of Students’ Anthropomorphism in Science

Taber and Watts (1996) used the terms *strong and weak anthropomorphism* to denote the difference between the situation where anthropomorphism is used in a metaphoric sense, as a temporary placeholder for an explanation, and where it was considered to provide a sufficient form of explanation. They considered anthropomorphic language *weak* when the user is aware that they are *deliberately* using such a mode of speech and does not intend to offer a mechanism. Similarly, Zohar and Ginossar (1998, p. 680) distinguished between what they called anthropomorphic/teleological *formulations* and anthropomorphic/teleological *explanations*, where the former are seen as modes of speech. Such modes as metaphors and pictorial language are not intended as formal explanations, but merely as practical ways to express oneself. Talanquer (2007, p. 866) suggests that anthropomorphic formulations have heuristic value and aid students in structuring their knowledge, to 'help the students organise their knowledge around major ideas with significant explanatory and predictive power'.

Taber and Watts (1996) suggested that weak anthropomorphism is productive when used as a means of helping students become familiar with abstract concepts in science. From a constructivist perspective, meaningful learning requires the learner to actively make sense of new ideas in terms of their existing conceptual resources – and analogies and metaphors can support this. What Taber and Watts referred to as *strong* anthropomorphism, however, is seen as providing teleological explanations, being the actual cause of an event (i.e. it happens because of this), rather than intended to provide a way of starting to think about a concept (i.e. it is a bit like this).

Therefore, whether anthropomorphic explanations act as learning impediments or not is seen as depending on *the status the student places on the explanation*. If seen as a satisfactory explanation, then the individual may have little reason to develop more sophisticated explanations. However, if the explanation is only used to familiarise learners with 'a descriptive level of understanding of atomic-level phenomena through mental role-play and empathy' (Taber and Watts 1996, p. 565), then the authors argue that anthropomorphist explanations should disappear as learning progresses. Taber and Watts raised the question, however, of whether with habitual use, such modes of speech may shift from a function of *standing in* for an explanation to *acting as* explanation. That is, they conjectured that it was possible that what starts as a kind of *placeholder* for a missing explanation comes with repeated use to *take the place of* the explanation. This is an important issue in science education, as science teachers should be advised on whether (or perhaps more likely, when) it is appropriate to encourage students' use of anthropomorphic language, or whether (or when) teachers should actively seek to shift student language away from such formulations.

Context of the Study

In the present study, we explore the level and nature of anthropomorphism used by learners in our sample of upper secondary Swedish students of chemistry over a year of study and in particular consider whether there are indications of the status such anthropomorphic explanations have for the students. The results presented here derive from a project designed to describe how Swedish upper secondary science students develop their understanding of key concepts for matter and phase change (Adbo and Taber 2009). The present study draws upon longitudinal research undertaken with a group of eleven 16–18-year-old students who were attending the upper secondary high school natural science programme in a Swedish town. This programme extends over a 3-year period and can have a varying structure regarding the timing and sequencing of the natural science subjects included.

We have previously reported that the limited prescription of the expected treatment of subject matter in the Swedish curriculum can lead to large variations in the content of formal teaching within, as well as between, different compulsory and upper secondary schools (Adbo and Taber 2009). One effect of this lack of specification is that teachers commonly choose to follow the textbook of their choice when planning and carrying out their teaching. The teacher who participated in this study chose to structure the content of the chemistry course in accordance with the outline of the course textbook.

Methodology

A longitudinal interview study, stretching over the first year of chemistry, was undertaken. Permissions (from the school authorities) and informed consent were obtained following standard ethical procedures. Eleven of twenty-one students in the class volunteered to be interviewed for the study. Data were collected using semi-structured interviews. Recordings of the interviews were then transcribed and analysed. In order to gain insight into the structure and timing of the formally introduced concepts, nonparticipant classroom observations were performed throughout the entire first year. In all, 49 h of 'theory' classes were observed. Observations were made in the form of notes concerning content and student verbal activities (e.g. number and direction of questions and answers).

Student Context

Results presented here derive from the first year of the students' course (when they were aged 16–17), where the students were participating in the following natural science subjects: chemistry, mathematics and biology. (Physics is not studied until the second and third year.) The first year chemistry course included introduction to chemistry in general, chemical bonding, introductory acid-base theory, stoichiometry, organic chemistry, gas laws and thermodynamics.

Time allocated to the chemistry course totalled 86 h over the year. These hours were divided between laboratory exercises' and theory classes so that the students received 62 h of theory and 24 h of laboratory exercises in total for the first year. This meant that on an average weekly basis, chemistry was for the students composed of 2×40 min of theoretical classes and 40 min of laboratory exercises (laboratory exercises were combined into one 80-min class every second week). A summary of the main concepts and the approximate time of their introduction are presented in Table 1.

A full content analysis of the teaching observed, and of the relevant sections of textbook used as the basis for the course, is not possible within the constraints of the present chapter. However, the nature of the explanations presented to these students

Table 1 Sequence of formally introduced chemical concepts and timing of student interviews

Time of introduction	Concept	Concept content	Timing of interview session
Initial introduction (first week of school year, August)	States of matter (s, l, g)	Differences between particles in the different states as movement ranging from vibrations (s), more restricted movement (l) to free movement (g). Matter as ranging from a highly ordered arrangement (s), particles in arrangements with no long-term order, (l) to particles with no order to their arrangement (g)	
September	The general atomic model	Subatomic particles, their relative mass and charge; electrons in shells marked K, L, M, etc. Lewis dots for valence electron configuration	
September	The periodic table	History of its creation, periods and groups, general trends such as number of protons, valence electrons, ion formation, general description of group significant properties	Interview session 1
October	Chemical bonding	Ionic bonding, metallic bonding and covalent bonding, polar covalent bonding, electronegativity and four examples of molecules to visualise molecular geometry	
November and December	Chemical calculations	The mole concept, chemical equations, basic calculations	Interview session 2
January	Introductory acid-base theory	Acids and bases, concentration, basic calculations, pH scale, neutralisation, buffer solutions	
February	Introductory electrochemistry	Redox reactions, galvanic cells	Interview session 3
March	Introductory organic chemistry	Introduction to IUPAC naming of organic compounds	
April	Aggregation forms	Gas law, dipole bonding, van der Waals bonding, hydrogen bonding	
May	Energy	Energy	Interview session 4
First week of June (end of school year)	Modern materials	Development of ceramics, glass, etc. Introduction to polymers	

as canonical is certainly relevant when considering the origins of their explanations in the interviews reported below. Table 2 presents a summary of the key features of the explanations presented to the students participating in this study through their textbook, and through the teacher's own presentations.

Table 2 The main focus of explanations for phenomena as presented to the students in their textbook and teacher presentations

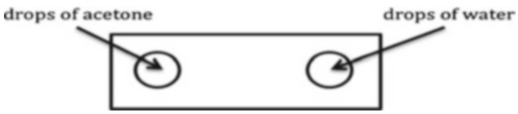
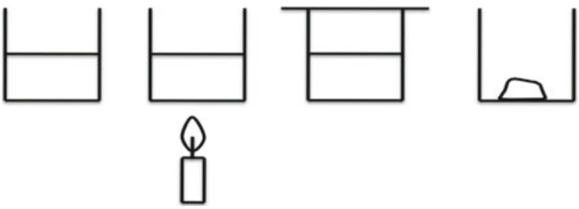
Theme	Focus of curriculum presentation
States of matter	Arrangement of particles
Chemical reactions	Reactions occur because atoms strive to achieve noble gas configuration; atoms want eight electrons in the outer shell
	Ionic and covalent bond formation is a consequence of the atoms striving to form noble gas configuration
Ionic bonding	Textbook presentation: Electrostatic forces due to attractions between opposite charges in ionic crystals – an ion 'surrounds itself' with oppositely charged ions. The bond is a force
	Teacher: Placed emphasis on electron transfer between specific atoms and charge of ions formed
Covalent bonding	Merging of electron clouds. Attractions between nuclei and electron density
	Equal 'sharing' of an electron pair
	Repulsion determines shapes of molecules
Polar bonding	The electron cloud is being attracted stronger by the nucleus of the more electronegative atom
Metallic bonding	Due to strong forces
	An electron cloud that belongs to the entire metallic crystal
Hydrogen bonding	Attractive force between molecules
Dipole-dipole bonding	Forces between molecules
van der Waals forces	Weak attraction forces between molecules, due to electrical charges and temporary irregularities in electron cloud geometries
Dissolving and solutions	In ionic solutions: attractions between ions and polar molecules; ions not being 'naked' as bound to solvent molecules
	In mixtures: relative strength of, e.g. hydrogen bonds
Evaporation	Energy of particles, overcoming forces with adjacent molecules

The second author carried out all observations and interviews. All interviews took place in Swedish and have been translated into English for this report by the second author. Veracity of translations was made by a native English speaker fluent in Swedish and by a native Swedish speaker fluent in English. Four interview sessions were undertaken with each of the students. Interview sessions were scheduled approximately 2 weeks after teaching of the focal topic had been completed and after the associated written examination. The results presented below derive from the 11 of the 21 students that chose to participate. The results presented here derive from 43 interviews (as one of the students did not complete the year).

Design of Interview Sessions

Interview sessions were semi-structured and questions were focused around items or schematic drawings, interviews-about-instances-and interviews-about-events (Gilbert et al. 1985). The students were provided with a paper and a pen on all of the

Table 3 Foci used in semi-structured interviews

Interview	Foci
Interview session 1	A vial with lid (representing the gaseous state) A bottle containing a liquid marked ethanol (representing the liquid state) A piece of metal and metal powder (representing the solid state)
Interview session 2	As foci for this interview two chemical reaction equations were chosen The focal equations were not balanced and the students were asked to assume the different states of the substances included. The first equation represented the combustion of methane forming carbon dioxide and water, and the second represented the precipitation of barium sulphate in solution of sodium, chlorine, barium and sulphate ions
Interview session 3	Sodium chloride crystals A solution marked with Na^{+} and OH^{-} A solution marked H^{+} and Cl^{-}
Interview session 4	Drops of acetone and water were placed on a piece of glass, as shown below, and left to evaporate:  Graphic images of: a container with a liquid; a container with a liquid and a candle as a heat source beneath it; a container with a liquid, the container having a lid; and a container with a solid substance: 

interview occasions and were invited to draw when needed. The foci presented included observable phenomena, samples of substances, images and chemical equations. Chemical equations were presented because they operate at the symbolic or representational ‘level’ (Johnstone 2000) and have a vital role in chemistry because they act as a means of mediating thinking about the macroscopic level where students can observe chemical phenomena, and the submicroscopic level which provides the basis for most theoretical explanations that chemists develop of those phenomena (Taber 2013). The focal items and schematic drawings that were used for the four interview sessions are presented in Table 3.

Analytical Procedures

The decision to explore student thinking in detail derives from the adoption of a constructivist perspective (Bodner 1986; Driver and Bell 1986; Glasersfeld 1989;

Novak 1993), which considers the learning of each individual to be somewhat idiosyncratic: being contingent upon specific features of that individual's current state of knowledge and understanding, as well as being channelled by the specifics of classroom teaching and the dialogue in that particular class. For each individual, classroom teaching and activity is interpreted in terms of their own internal mental 'learning ecology' (diSessa 2002; Taber 2001b), which has evolved through their previous life experience. As Pope and Denicolo (1986, p. 154) pointed out, such a research focus 'represents an epistemological stance consistent with the qualitative-interpretative approach'.

Accordingly, analysis involved examining student interviews, line by line, and attempting to understand the intended meanings of students' utterances within the context of the interview discourse (Kvale 1996), using an approach informed by grounded theory procedures (Glaser and Strauss 1967; Taber 2000). The analysis was therefore undertaken through an iterative procedure, whereby interpretations are revisited as analysis proceeds with a view to checking earlier interpretations in the light of increasing insight gained by ongoing emergence in the data (Strauss and Corbin 1998). When analysing data, the 'constant comparison' method provides a means for the analyst to ensure that the analytical categories being developed by the analyst best fit the data and to seek 'theoretical saturation' (Glaser and Strauss 1967; Taber 2003, 2009a). Comparisons were not only made within transcripts but also across individuals at the same interview stage and longitudinally through time for individuals.

Results

We report the findings chronologically, in terms of the four interviews during the year.

Student Explanations in the First Interview

At the time of the initial interview session (with its primary focus on the 'states' of matter), students had not been taught about chemical reactions during their upper secondary course. Nonetheless, nine of the students addressed chemical reactions and talked about why chemical reactions occur. One student (Jesper) offered a model of why atoms attach during reactions, which drew upon ideas of attractions between atomic components, and indeed a kind of interlocking mechanism. However, the other eight students able to offer ideas about reactions all used anthropomorphic language to some extent, as demonstrated in Table 4.

In most of these cases, their explanations explicitly related to the octet rule – reactions occurred because atoms wanted to obtain a full shell. The students used a variety of ways of phrasing their ideas, but commonly implied that reactions

Table 4 Student's anthropomorphic references in discussing chemical change during the first interview

Student	Explanation
Annika	Everyone *wants* to have a full outer shell…well if it *wants* to give one away from the outer shell it will, sometimes it *needs* energy
Bjorn	…then this electron can jump over to another one and form a new substance [Why?] I don't know it is one of these mysteries that scientists don't know why, since they have less electrons then it *wants* to take up more electrons or let go of one if they *think*…
Gustav	They *want* full shells, or balance…that depends on their inner *needs*, only two and then there is eight and then it moves on eight or eighteen I think it is. The electrons *want* to be even…[The balance is] like if one electron is missing then of course it *wants* one, and then it will take one from another. Another might *want* to let one go. The balance is between electrons protons and neutrons
Jenny	They *want* their outer shell to be full so that no more electrons can fit there
Johan	They share, they fill their K-shell, I believe then they are *happy* and it becomes hydrogen gas
Kanita	…they are drawn towards each other when they *want* a full shell. If it reacts with another substance then a new shell is formed and they won't have a full shell anymore and they *want* to have a full shell
Nichole	…they have reacted, they are pulled together…Because this one has properties that this one *wants*. They match each other well
Pernilla	[On being asked about phase transitions:] One can only see the transitions between states because one can see the molecule pushing things away or take things up… they push away electrons… Well it is like noble gases they *want* a full shell, but I don't know if that is a chemical reaction so that the substance changes
	[On being asked why reactions take place] They *feel* they *need* each other, they *see* that the other atoms have something they *want*…it could be an electron or a proton or a neutron or something. I don't know if energy has something to do with it. They are used for different things in different places and then the one that is most *interested* to have it merges with the other atom and they may *feel* that, I would *rather* be in this place

happened *because* of what atoms wanted. There are also references to what atoms need, what they think, what they feel, what they see, what they would rather, what interests them and what makes them happy. Another of the interviewees, who did not offer any ideas about chemical change (Hakan), referred to particles being able to 'float wherever they *want* to' in the context of the differences between the solid, liquid and gaseous phases.

As suggested above, anthropomorphism may be used to aid communication, and only meant in a metaphoric sense. There was some evidence from some of the student comments that they did not intend their anthropomorphism in the 'strong' sense of providing a causal explanation. So although Bjorn referred to atoms wanting to lose or gain electrons, he also thought that scientists did not really know why reactions occurred. In his case, we would suggest he used 'weak' anthropomorphism, which could act as a placeholder, until scientists solved (what Bjorn considered) the 'mystery' of why reactions occurred.

As well as the anthropomorphism presented in Table 4, Pernilla referred to how electrons 'would *need* to get close to the atomic nucleus sometimes to exchange information' as 'electrons and the protons may *need* to communicate with each other'. However, despite the quite extensive anthropomorphism in her explanation in Table 4, she also interjected the thought that she did not know 'if energy has something to do with it', suggesting that although she seemed comfortable with anthropomorphic accounts, she was at least open to these not providing a fully adequate explanation.

In summary, then, amongst these 11 upper secondary students who had opted for the science stream, two did not seem to have considered why chemical reactions occurred, one offered an idiosyncratic mechanistic account and eight offered anthropomorphic accounts – of which six of our interviewees gave no sense of suggesting such accounts were considered inadequate.

Student Explanations in the Second Interview

In the second interview, after formally studying chemical bonding as a topic in their high school course, the students were asked about the equations for two reactions. Table 5 reports how the students explained why the reactions occurred.

As in the first interview, student responses were commonly phrased in anthropomorphic terms (see Table 5) and generally based around notions of atoms wanting to obtain full shells or noble gas configurations. In this round of interviews, *all* 11 students provided these types of accounts.

So our interviewees suggested (see Table 5) that species such as atoms or molecules:

- Want: to get rid of electrons, more valence electrons, noble gas configuration, high status, full valence electron shell, to be stable, to go, to even out, to get together, a neutral charge
- Do not want to leave
- Need: to be a gas, to find another substance
- Strive: to be noble gases, to even out
- Try to look like noble gases
- Think they have full outer electron shells
- Like each other
- Were safe
- Search for others
- Trick: each other, themselves
- Give/send away electrons
- Feel

However, again there were signs that not all of these students were satisfied with the accounts they were able to offer. Hakan, one of the students who had offered no explanation of reactions in the first interview, here talked about atoms thinking, feeling and tricking each other, but realised that atoms are not really sentient

Table 5 Student's anthropomorphic references in their explanations for why reactions occur in interview 2 (after studying bonding at senior high school level)

Student	Explanation for reaction: combustion of methane	Explanation of reaction: double decomposition
Annika	I don't know why they really happen but they *want* noble gas configuration… They merge so they *think* that they have a full outer electron shell	It *wants* to be like this having a full valence electron shell
Bjorn	…Why it happens it has to do with electrons, it *wants* to be a stable atom	These are whole molecules that are missing, well this one *wants* two more valence electrons to become stable and *it will probably search* for other whole molecules that have two extra electrons
Gustav	…the oxygen has a larger nucleus so it attracts more and hydrogen is really light so *they both trick each other*, these *don't want* to leave since they both *think* that they have full shells so they do not *want* to leave – this one thinks that it has a full shell [How do they know?] It is not too much so they *want* to go and not too little so they get even, or – this is difficult	This one has one electron less and this one, one too many and then they *want* to even it out, they *strive* to even it out [as] these ones *want* to get together – maybe it, maybe because chloride *needs* to be a gas. I don't know, in the book it said Cl_2 it may have to be a gas so that it can react more easily
Hakan	Well they *trick* themselves, hydrogen has one here and then one here, and then they *think* that they are full (pause). I don't know how because they do not have a brain so *they can't think* but they *feel* (pause) it must have something to do with energy or balance… balance between each other	They have different charges, that could be it, but I don't know – they *want* a neutral charge, and this one is plus two and this one plus one and they cancel out and they become neutral and then they merge in to an ionic bond
Jenny	They *want* a full shell	It has *given* away a valence electron, it has one extra proton, or neutron or, one less electron that gives a positive charge. [What happens?] Both these have charges and this is positive and this is negative and then they will be drawn to each other
Jesper	They *want* full shells	[No anthropomorphic references]
Johan	The electrons are attracted to them somehow, but I don't really know, both of them want the electrons… Because they both *want* to have noble gas configuration	They also *want* noble gas configuration, then they *send* one electron away or they take one up. I don't know but they must get close to each other. I guess that it does not require a lot of energy, first they must become ions and to become that they *need* to find another substance first that they can take electrons from or give electrons to, and then they might need energy

(continued)

Table 5 (continued)

Student	Explanation for reaction: combustion of methane	Explanation of reaction: double decomposition
Kanita	It has something to do with electrons again, they *want* noble gas configuration, a full valence shell	If they have like Na [sodium] it is easier for them to *give* one electron away then to react with another substance. Then they become more like a noble gas. It has to do, it has to be, because this one has a positive charge and this one has a negative charge and together they will be neutral and have no charge at all
Louise	[The combustion of methane occurs] because this one [CH_4] has a positive charge and this one has a negative charge (O_2) and this one (O_2) *wants* to get rid of its valence electrons… [because] it *wants* noble gas configuration	Because they *want* noble gas configuration, it *wants* a full outer shell
Nichole	When they meet, some substances *like each other* more than others do… because the number of valence electrons fit so well together … [as] they can fill their outer shells	They would attract each other since this one has two plus and this one has two minus and then they fit since they get full shells and this one has one plus and one minus they get noble gas configuration and then they are *safe*, well safe, they get a full shell two plus and two minus then they are not charged anymore, and then they are stable and do not react with any other substance – or yes they do, but it is just stable
Pernilla	They, all of them, *want* to have high status and they *strive* to be noble gases since that is the best and then they try to look like noble gases as much as possible	[No anthropomorphic references]

(as ‘they do not have a brain’) and suggests that there must be some other explanation in terms of energy or ‘balance’. Annika, Johan and Bjorn all gave anthropomorphic explanations that were accompanied by the provisos that they did not know what was *really* happening. We take this as evidence that for these students, this was a form of weak anthropomorphism – a form of account that had some narrative quality, but which they recognised did not satisfy as a formal explanation. In Bjorn’s case, a later exchange in the interview suggested that he could think about chemical bonding in terms of forces, of basic physics, as ‘all atoms have an ability to attract both electrons and the other atoms’. So Bjorn was at least aware that chemical bonding could be understood in terms of physical interactions, even if he had not made the connection that reactions, leading to changes in bonding, may occur *because of* these forces.

Student Explanations in the Third Interview

At the time of the third interview, students had been studying acids and bases and electrochemical reactions – both topics included reactions involving solutions. During the interview, the students were asked about solutions and solubility in order to gain insight into their progression regarding chemical bonding. In particular, they were asked why some substances dissolve. The overall set of student accounts of dissolving were quite different in nature to the explanations of chemical reactions offered in the first two interviews. In general, the students had limited, or vague, understanding of why some materials dissolve in some solvents (but others do not). A number of students simply acknowledged that they had no explanation (Annika, Bjorn, Gustav, Hakan). Kanita and Nichole referred to types of reactions, without explaining why such a reaction might occur. Other students attempted to offer an account of the process, and a number (Jenny, Jesper, Louise) suggested some form of force or attraction was involved. These responses did not give the impression of being well-established ideas in students' thinking, but more the creation of feasible reasons in the context of the interview. Indeed, Louise referred to having never before come across the question of why things dissolve.

What is noticeable is that there were few attempts to explain the process of dissolving in terms of the needs and wants of atoms, molecules or ions. The exception was Pernilla, who suggested that 'it is always about where they get the best opportunity to make, to do things, the qualities they really *want*'. She seemed to use this principle in a *tautological* sense: the atoms always wanted more status, so in this case the dissolved form must have more status:

> I have no idea how that would work – they change the water, they divide and it is always about where they get the best opportunity to make, to do things, the qualities they really *want* and it is more status, things like solubility…[the water] divides to hydrogen and oxygen.

Student Explanations in the Fourth Interview

During the final interview session of the year, the students were presented with, amongst other things, a microscope slide where a few drops of water were placed beside a few drops of acetone that quickly evaporated. The students were then asked to explain the difference between the two. In the interview, pupils discussed the different phases of matter, how and why phase changes such as evaporation occur, and the nature of the interactions between molecules.

One of the most salient features of the students' explanations in the fourth interview was the common use of anthropomorphic references, which – after the limited use in the third interview – were now again well represented in students' accounts of phase changes and intermolecular interactions (see Table 6).

Table 6 Student's anthropomorphic references in discussing phase change and intermolecular bonding in the fourth interview

Student	Anthropomorphic elements in student explanations
Annika	[On evaporation]: If it is water,… They *want* to get as far away as possible, well they get warm and then they move away a bit…
	I think [intermolecular bonding in a liquid] has to do with number of electrons, they *want* to fill their shells
Gustav	[On liquids] these [attachments] are weak and then the energy comes from the surroundings and then they do not *want* to be stuck there and they move off
	[On solids] each molecule has its own place … there is a system there they have their own place. … they *want* to bond and be stable and I don't know at some stage when they are neutral and do not *need* any other around it. It has its place like a noble gas and it does not *need* anyone
	[On bonds between molecules] they talk of them as having arms but they are in fact electrons that latch on to get a full shell. It is an attraction between nuclei or a *striving* to get a full shell
	Nature always *wants* to even things out so it gets equal of everything so it may *want*, if the atom can go in to a more stable format or a more stable form then it has at the moment then it will
	When a liquid takes energy then it *wants* to become a gas
Hakan	[On evaporation] They *want* more space and here there is more space and there is no lid so they move into the air
	They need a larger surface, they *need* more space, they move faster
	[On liquids] They may *want* to move more. … The warmer it gets the more energy they get and then they *want* to move more so then it first is liquid and then turns into gas
	[water molecules were drawn together because] It is the valence electrons they *want* eight and then they share and then it *feels* like they have a full shell or hydrogen takes two … I don't know why they *want* a full shell, it is what they *strive* for but I don't know
Kanita	…everything has a structure [depending upon] how many bonds there are in-between and what atoms there are. … It depends on the ones that want noble gas configuration, how far they are from it, some *need* four electrons and then some may only *want* one and it is different
Jesper	[A liquid not observed to evaporate] doesn't since it does not *need* it, there is no demand for it
Louise	[On evaporation] They are so light that they *want* to move upwards and then pressure is formed
Nichole	Oxygen …is negative…Since the electrons, it has more electrons then, it is sort of, there are too many electrons, or wait, now it gets difficult, I have to think, this one *wants*, and this one do not doesn't have enough, it *wants* electrons in the outer shell so it has two less and this one comes and sits here and then there is a full shell
	[On liquids] They always *strive* to fill their outer shell, they *want* to be noble and stable
Pernilla	[Water that did not evaporate] is *content* with how it looks, it is either unsaturated or I can't remember what it is called when it is new, or how it looks it does not *feel* like reacting
	[What is the bond?] Between the atoms it is that they *want* to be more noble, they *want* something better. … they are *alive* too
	Molecules do not make anything, they can't build anything, so they form chains so they build things it is some force they *want* to expand and they might not *need* as much energy when they are together they *want* to build things

Table 6 includes comments from eight of the ten interviewees (Bjorn had left the course at this point and so was not interviewed). Atoms and/or molecules were said by these students:

- To *want*: to get apart, to fill their shells, to bond, to be stable, more space, to move more, eight electrons, a certain number of additional electrons, to move upwards, to be noble/more noble, something better, to expand, to build things
- To *not want* to get stuck
- To *need*: a larger surface, more space, a certain number of additional electrons
- To *not need*: anyone, as much energy, to evaporate
- To *strive* for a full shell
- To *feel* like they had full shells
- To *not feel* like reacting
- To *be content* with how it looks
- To be *alive*

It seems the relative lack of anthropomorphic references in the third interview did not reflect any general shift away from using such forms of explanations to make sense of chemistry at the submicroscopic level. Rather, the context of phase change elicited suggestions that were commonly couched in anthropomorphic language, whereas dissolving did not (something we consider further in the discussion).

A noticeable feature of student explanations at the fourth interview session of the year was the variation in explanations provided. Indeed, all these students to some extent offered multiple explanations for phase change and intermolecular interactions. Although anthropomorphic explanations were common, they were often used alongside explanations based upon physical concepts such as charge and gravitation. Even the two students who did not use anthropomorphic references in the fourth interview (Jenny and Johan) were not able to offer a single coherent account of phase changes.

When considering why evaporation occurred, several of the students gave the impression that they did not see separating the molecules from one another was a sufficient explanation for the gaseous state. Jenny invoked 'attractions from above… [from] the air' to explain this. A number of other students explored, if sometimes tentatively, the notion of evaporation being a kind of reaction:

- Hakan: Evaporation 'might have something to do with the contact to air…it might react with the air somehow, no I don't know'.
- Kanita: Propanone 'could have reacted with oxygen and then formed something else instead so it has disappeared'.
- Pernilla: Evaporation occurred because 'it reacts with the air or something in the air' as 'some substances react with air'.
- Nichole: 'It might be that reactions occur in the liquid with air maybe'.
- Jesper: 'Maybe it [propanone] reacts with the air somehow… [whereas] the other one, it [water] doesn't…'
- Louise: 'It may have reacted with air'.

Other interviewees simply offered anthropomorphic accounts of evaporation. So Annika evoked molecules that 'want to get as far away as possible, well they get warm and then they move away a bit'. Gustav explained that some liquids readily evaporate because they have 'weaker bonds in-between so they break easily', but again did not feel this explained why a vapour was formed: rather the bonds 'are weak and then the energy comes from the surroundings, and then they do not want to be stuck there and they move off'. Although Gustav was able to describe how 'energy causes the molecules to vibrate and then the bonds become weaker and they take off', he still couched this in anthropomorphic terms: 'when a liquid takes energy, then it wants to become a gas'.

Hakan, having considered, and apparently dismissed, the notion of evaporation being due to 'contact' with the air, offered the anthropomorphic explanations that 'they may want to move more' and 'they want more space and here there is more space and there is no lid so they move into the air'. However, it became clear when he was asked how the particles knew this, that this was weak anthropomorphism standing in place of any satisfactory explanation:

> They don't know that, but when something gets warm it takes more space – I don't think that they know. They have no brain so they can't think it. They need a larger surface, they need more space, they move faster. I don't know how to explain that.

Explanations of the bonds between molecules in a liquid were often couched in anthropomorphic terms. So Pernilla described 'an energy attraction between the molecules' which she explained as 'they want to be more noble, they want something better'. Pernilla explained her use of this anthropomorphic construction as 'one thinks from our own perspective: it is easier to imagine it from a human perspective and they are alive too'. Adopting such a perspective, she suggested that there were bonds between molecules as 'one molecule does not make anything, they can't build anything, so they form chains – so they build things…when they are together they want to build things'.

When it came to explaining intermolecular bonding, some students tended to rely on their knowledge of intramolecular bonding types. This seemed quite significant for their use of anthropomorphic language, where they thought about intramolecular bonding in octet terms (as found in interviews 1 and 2). Kanita seemed to be referring to atoms when she described 'some need four electrons and then some may only want one' which 'depends on the ones that want noble gas configuration, how far they are from it'.

Nichole thought that the difference between phases must be related to 'the bonds' and made references to 'different charges' and some bonds being 'polar'. However, Nichole was only able to explain bonding in terms of the octet explanatory principle, anthropomorphically: 'this one wants… it wants electrons in the outer shell so it has … a full shell'. For Nichole 'the molecules or particles in the fluid' attracted each other because 'they always strive to fill their outer shell [as] they want to be noble and stable'.

In some cases, there were again clear signs that our interviewees were using 'weak' forms of anthropomorphism, that is, anthropomorphic explanations that acted as placeholders and were not considered fully satisfactory explanations. For Hakan, the bonds that held together structures were the familiar categories of 'ionic bonds and covalent bonds and then there is metallic bonds as well'. Given this, he explained this bonding in terms of 'how many different valence electrons they have' as 'they want eight and then they share, and then it feels like they have a full shell'. When asked why the particles would want a full shell, Hakan suggested this was due to 'some force', but when then asked to specify what this was, he could not develop this line of thought and instead resumed his anthropomorphic references: 'I don't know why they want a full shell, it is what they strive for, but I don't know'. The sense here is that Hakan was quite aware that this 'striving' was not an adequate explanation, but was not sure what underlying physical force might be responsible.

Similarly, Annika suggested that the reason water molecules were attached 'has to do with number of electrons they want to fill their shells'. This seemed an example of weak anthropomorphism, as when she was challenged to explain what she meant by 'want', she replied: 'They want all power, no, I don't know'.

Similarly Gustav appeared to be reaching for an explanation of intermolecular bonding that was based around forces, but to fall back upon the language of atoms wanting to obtain full shells. He explained this in hesitant terms: 'I don't know, they want to bond and be stable, and, I don't know, at some stage when they are neutral and do not need any other around it [then] it has its place like a noble gas and it does not need anyone'. However, when asked in general about bonds between molecules, Gustav offered a somewhat different account:

> It is a kind of positive and negative charge, a form of attraction that effects them on one side or the other, and makes them hold with some form of gravitation or some kind of attraction from the nucleus – they talk of them as having arms but they are in fact electrons that latch on to get a full shell. It is an attraction between nuclei or a striving to get a full shell … Nature always wants to even things out so it gets equal of everything so it may want, if the atom can go into a more stable format or a more stable form than it has at the moment, then it will.

So Gustav mixed reference to physical forces, with what he recognised as anthropomorphic metaphors ('arms' that were actually electrons), and his own references to teleological and anthropomorphic drives: tendencies to 'even out', and atoms striving to fill their shells.

Deconstructing student comments from the interviews can give the impression of discrete responses that fit into simple categories, but as suggested above, most students' responses were multifaceted. This seemed to reflect the lack of access to a single satisfactory explanatory scheme to make sense of phases and phase changes. This is illustrated well by Louise, who suggested that solids 'are packed very hard really tight and there are really strong bonds so they hold together very well', and like a number of peers, as reported above, sought to draw on familiar forms of bonding to explain what is occurring during evaporation: 'the heat may cause the bond to weaken, the covalent and ionic bonds [sic] are weakened, and they are transformed to gas'. Yet, again in common with a number of her peers, Louise did not seem to consider the removal of bonding as a sufficient explanation for the gas phase and suggested that the molecules 'are so light that they *want* to move upwards'.

Louise was clearly frustrated at not knowing how to explain why the propanone, but not the water, was observed to evaporate: ‘I try to relate it to an everyday occurrence, why liquid dries after a while, I don’t know if it has to do with bonds that this one holds together better or if it has a lower temperature – no this is so strange, I almost get angry’. She considered that different types of bond might be involved, but this avenue is abandoned as she only knew about the bonding in solids: ‘this may be stronger than an ionic bond, but it is not a solid’. Louise then, reflecting a number of her peers, suggested that ‘it [propanone] may have reacted with air and this [water] does not’, but without appreciating why reactions took place she had little basis for such a discrimination: ‘this one must have a greater need to react’. It seems Louise had offered available physical options (bond strength; reactivity) from her explanatory repertoire, and when these did not satisfy her, fell back upon the anthropomorphism of the relative ‘need to react’. Yet, this is a weak form of anthropomorphism, apparently acting as a placeholder for a more canonical form of explanation: as when she is asked what this need would be, she suggests ‘it must be some form of charge in them’.

Discussion

In this chapter, we have explored the extent and nature of anthropomorphism used by our sample of upper secondary Swedish students of chemistry and in particular considered indications of the status such anthropomorphic explanations have for the students. We are aware that research undertaken in the context of one class of students cannot be assumed to generalise to other learners, especially those studying in different educational contexts. However, our findings are consistent with the work of others who have noted students’ use of anthropomorphism in their explanations of natural phenomena (Taber and Watts 1996; Talanquer 2007; Zohar and Ginossar 1998).

Our first conclusion is that there was a high level of use of anthropomorphic language in the explanations that were offered by these 16–18-year-old Swedish science students when asked about basic phenomena met in chemistry – such as states of matter, phase change, dissolving and reactions. In most of these contexts, with the exception of dissolving (a point we return to below), anthropomorphism seemed to be a key feature of student explanations.

Despite these students studying chemistry at quite an advanced level, their discussion of the ‘behaviour’ (sic, a common chemical term that can be considered itself to be an anthropomorphic metaphor) of entities posited at the submicroscopic level in the theoretical models so central to modern chemistry was commonly phrased in terms of the ‘needs’ and ‘wants’ of atoms and molecules. This reflects similar findings with English students of comparable age and educational level (Taber 1998; Taber and Watts 1996).

While it is fairly simple to identify such anthropomorphism, it is not always so clear how students are using anthropomorphic language: that is, whether such language is intended literally (implying that anthropomorphic explanations were considered satisfactory) or reflects either a means of communicating ideas found difficult to express or simply a best attempt to provide some kind of an explanation where the student concerned was aware that they could not offer a scientifically adequate response to our questions.

There were certainly many examples in our study where students seemed to offer anthropomorphic explanations without any hint that these might be considered unsatisfactory. This would be what Taber and Watts (1996) call *strong anthropomorphism*. This is particularly the case in many of the examples of students referring to atoms 'needing' to obtain full shells. This seems to be a very common explanatory principle used by students in chemistry (Taber 1998), and indeed it has been suggested that chemistry teaching may often be presenting this as if a canonical scientific idea (Taber and Tan 2011). As students in our sample were commonly using these ideas in interview 1, prior to formal teaching at this level (see Table 1), it seems quite likely that this represents thinking acquired during earlier compulsory schooling and which had become so habitual that it was seldom questioned. Ideas about bond formation and chemical change being driven by atoms needing full shells seem to fill an *explanatory vacuum* (in that no scientific rationale is offered in introductory chemistry courses) and with repeated use, and lack of critique, can become well established long before the canonical explanations are met.

However, there were also many examples where the context of students' anthropomorphic references leads us to suspect that this type of language was being used in much less fixed ways. We have highlighted examples where anthropomorphic explanations were offered tentatively, often with caveats that the student was not really sure what the correct explanation was.

Learning Chemistry in an Explanatory Vacuum

The focus of the present report is the extent and nature of these Swedish upper secondary students' use of anthropomorphic language in explaining their understanding of aspects of chemistry. That language will in part reflect the conceptual resources they bring to upper secondary chemistry from earlier learning. It will also be influenced by the explanations, and the forms of language used, in the teaching they experience. We provide an overview of the focus of the teaching of the topics considered here as met by the interviewees of the present study in Table 2.

According to constructivist notions of learning (Ausubel 2000; Glasersfeld 1989; Taber 2009b), learners can only make sense of teaching in terms of existing conceptual resources (Hammer 2000; Smith et al. 1993), that is, ideas that they already have available. Approaches to designing instruction based upon structural analyses of subject matter, intended to ensure that material was presented to learners to allow stepwise learning (Bruner 1960; Gagné 1970), may be undermined by learners failing to make expected links and/or making unintended links with prior knowledge (Taber 2001a). When teaching is not sequenced to reflect the logical structure of the subject matter, there is even more scope for learners to misconstrue presented material.

A key aspect of any science is the development of theoretical models that can be used to explain and predict phenomena of relevance to that scientific field. Yet, in chemistry, the models and theories are often quite abstract and complex, whereas the phenomena themselves are often readily observable and accessible. This is certainly the case in terms of the states of matter and such changes as dissolving and evaporation.

In our study, we asked students why substances dissolved and why evaporation occurred. These are basic and familiar phenomena, but these advanced secondary students did not demonstrate a strong grasp of the chemical models that are used to explain these phenomena. As shown in Table 2, both of these topics had been presented in terms of physical principles – the forces between particles such as ions and molecules. In general, our transcripts record students seeking to invent mechanisms and explanations in situ, drawing upon the conceptual resources they had available. Often, they clearly recognised the limitations of their suggestions, and it was common for them to shift from one idea to another. In some cases, students' intuitions impeded progress – so although from a scientific perspective, the breaking of intermolecular bonds is (in the context of basic kinetic theory) a sufficient explanation for evaporation, our students commonly sought some additional factor – such as reaction with the air or the molecules' desires to have more space. Where students had limited conceptions of the nature of intermolecular bonding (despite having been taught these concepts by interview 4, see Tables 1 and 2), they not unnaturally tried to use bonding concepts they were familiar with such as covalent, ionic and metallic bonding.

Commonly, our interviewees' explanations of both dissolving and evaporation were tentative, multifaceted and fragmented – suggesting that the conceptual resources they had available to draw on were largely inadequate for the job. One striking difference, however, was that while many of the resulting attempts at explaining evaporation had strong anthropomorphic features, this was rarely the case with dissolving. We can only offer a partial explanation for this. In the fourth interview, the focus on intermolecular bonding seemed to act as cue for thinking about intramolecular bonding, which was already generally understood in anthropomorphic terms. Also, in trying to explain the evaporation of propanone (when water did not seem to evaporate over the same timescale), quite a few of our interviewees invoked ideas about chemical reaction, which again was already understood as being due to atoms wanting to fill their shells.

However, in the context of being asked about dissolving, few students were provoked to refer to chemical bonding or reactions. At one level, this seems quite odd, as dissolving requires (like evaporation) bond breaking, as well as the formation of new bonds between solute and solvent. Intermolecular bonding, hydrogen bonding, dipole-dipole interactions and van der Waals forces were presented during teaching in terms of the action of forces between molecules (see Table 5). However, concepts of intermolecular bonding were only met *after* interview 3, and the availability of *the general notion* of there being bonds between, as well as within, molecules seems to have facilitated avenues for developing explanations in interview 4 that were not generally available to these students in interview 3. That there were so few references to intermolecular bonding in interview 4 which adequately matched the nature of these types of bonds may well reflect a point raised by Taber (1998) –once students have come to associate bonding with atoms acting to obtain full shells, this can impede understanding of those forms of bonding which cannot be explained in these terms.

The Full Shells Explanatory Principle as a Pedagogic Learning Impediment

Before our sample of students met the topic of chemical bonding at upper secondary level (i.e. in interview 1), there was a strong tendency to look to explain reactions in terms of atoms seeking to fill their outer electron shells. That this idea is so common (see Taber, "A Common Core to Chemical Conceptions: Learners' Conceptions of Chemical Stability, Change and Bonding", this volume) suggests that teachers in introductory chemistry classes explain chemical reactions in these terms or at least in ways that encourage this way of thinking. In the present study, we found that this form of explanation was even more prevalent after teaching about chemical bonding at upper secondary level.

This is not surprising given that even at this more advanced level, students in our sample were explicitly told that reactions occur because atoms strive to achieve noble gas configuration (see Table 2). So even though covalent, ionic, polar and metallic bonding models were all presented primarily in physical terms – that is, in terms of attractions, of forces between charges – this was in the context of the incongruent idea that bonds formed because atoms 'want' eight electrons in their outer shell. Given this anthropomorphic explicit teaching model, it is perhaps not surprising that students explained the combustion of methane and the precipitation of barium sulphate in these terms (despite, in both cases, such an explanation being completely illogical, as there were no changes in the number of outer shell electrons in any of the atoms or ions involved in these reactions).

It has been argued that when this idea of atoms striving to fill their shells is presented in teaching, it may be adopted by students and act as a 'pedagogic teaching impediment' (Taber 2005) which interferes with effective learning of more scientifically sound ideas, and research in Singapore with graduates preparing for teaching suggests that study of chemistry at university level does not reduce incidence of this alternative conception (Taber and Tan 2011). This may explain why the teacher of the class studied here offered students an anthropomorphic explanation for why reactions occurred and bonds formed, even though it was not consistent with the models of bonding being presented. It seems difficult to break this cycle of teaching and learning in terms of the needs of atoms, and this is one of the considerations that has encouraged Levy Nahum and colleagues to argue that radical new approaches to teaching the bonding topic is needed in schools (Levy Nahum et al. 2007). Certainly the students in our present study tended to readily accept this anthropomorphic form of explanation for bond formation and to extend it to contexts of intramolecular bonding.

How Does 'Weak' Anthropomorphism Develop?

This is just one intriguing aspect of our findings, leading us to suggest that the general topic of students' anthropomorphic explanations in science deserves more research attention. In particular, Taber and Watts conjectured that weak anthropomorphism had potential to either facilitate the development of scientific ideas (when it is understood as a temporary and not fully satisfactory form of explanation, but offers a way to conceptualise an abstract concept) or to impede such development (when it 'hardens' into a habitual way of thinking about a phenomenon). In our sample of Swedish students, ideas about atoms needing or wanting to obtain full shells would seem to have already hardened and to be readily triggered in any question that seemed to be about bonding or chemical reactions.

We wonder, however, about some of the more tentative anthropomorphic explanations that were offered by our students, often with provisos or hedges to act as potential disclaimers, or as phases of trying out different ideas during ongoing attempts to construct an explanation in situ in response to our questions. In the latter context, anthropomorphic formulations were often segued with references to the potential relevance of such notions as charge, energy or gravitation. A key question here is how such explanations under construction evolve in student thinking over time. This suggests that studies that repeatedly elicited such explanations for a fixed set of phenomena over a timescale of days, weeks and months could be very informative (cf. Opfer and Siegler 2004). The findings of such studies could be very useful in advising teachers on how they should best respond to students' anthropomorphic explanations in chemistry.

Our present study suggests that an explanatory vacuum regarding the rationale for chemical bond formation, and chemical reactions, in Swedish compulsory school science encourages the adoption of anthropomorphic formulations that are 'strong' (and so accepted as a satisfactory form of explanation) by the time students enrol in upper secondary science. Such scientifically inadequate formulations are offered as explanations in relevant contexts (why reactions occur) and are also adopted in inappropriate contexts, even after presentation of the scientific models (intermolecular bonding). In the present study, this would seem to have been encouraged by the retention of the anthropomorphic idea that bonds form because atoms strive to fill their shells as a teaching model, presented alongside scientific models in terms of bonds as attractions due to electrostatic forces.

However, we also found students using anthropomorphism creatively, trying out different available ideas in situ to construct new explanations for phenomena. Here such suggestions were usually tentative and could in principle do useful work to support visualisation of, and familiarisation with, abstract ideas, and filling in for more technical concepts until they become available. However, if, instead, a temporary and tentative notion transforms into a habitual way of thinking, it would then come to stand in place of (rather than standing in for) target learning. Further research is needed to see if such uses of anthropomorphism ultimately facilitate or impede the development of scientifically acceptable ideas.

References

Adbo, K., & Taber, K. S. (2009). Learners' mental models of the particle nature of matter: A study of 16 year-old Swedish science students. *International Journal of Science Education, 31*(6), 757–786. doi:10.1080/09500690701799383.

Ausubel, D. P. (2000). *The acquisition and retention of knowledge: A cognitive view*. Dordrecht: Kluwer Academic Publishers.

Bodner, G. M. (1986). Constructivism: A theory of knowledge. *Journal of Chemical Education, 63*(10), 873–878.

Bruner, J. S. (1960). *The process of education*. New York: Vintage Books.

diSessa, A. A. (2002). Why "conceptual ecology" is a good idea. In M. Limón & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 29–60). Dordrecht: Kluwer.

Driver, R., & Bell, B. (1986). Students' thinking and the learning of science: A constructivist view. *School Science Review, 67*, 443–456.

Gagné, R. M. (1970). *The conditions of learning* (2nd ed.). New York: Holt, Rinehart & Winston.

Gilbert, J. K., Watts, M. D., & Osbourne, R. J. (1985). Eliciting students views using an interview-about-instances technique. In L. West & L. Pines (Eds.), *Cognitive structure and conceptual change* (pp. 11–26). Orlando: Academic Press, Inc.

Glaser, B. G., & Strauss, A. L. (1967). *The discovery of grounded theory: Strategies for qualitative research*. New York: Aldine de Gruyter.

Glasersfeld, E. (1989). Cognition, construction of knowledge, and teaching. *Synthese, 80*(1), 121–140.

Hammer, D. (2000). Student resources for learning introductory physics. *American Journal of Physics, 68*(7-Physics Education Research Supplement), S52–S59.

Johnstone, A. H. (2000). Teaching of chemistry: Logical or psychological? *Chemistry Education Research and Practice in Europe, 1*(1), 9–15.

Kallery, M., & Psillos, D. (2004). Anthropomorphism and animism in early years science: Why teachers use them, how they conceptualise them and what are their views on their use. *Research in Science Education, 34*, 291–311.

Kvale, S. (1996). *InterViews: An introduction to qualitative research interviewing*. Thousand Oaks: Sage.

Levy Nahum, T., Mamlok-Naaman, R., Hofstein, A., & Krajcik, J. (2007). Developing a new teaching approach for the chemical bonding concept aligned with current scientific and pedagogical knowledge. *Science Education, 91*(4), 579–603. doi:10.1002/sce.20201.

Novak, J. D. (1993). Human constructivism: A unification of psychological and epistemological phenomena in meaning making. *Journal of Constructivist Psychology, 6*(2), 167–193. doi:10.1080/08936039308404338.

Opfer, J. E., & Siegler, R. S. (2004). Revisiting preschoolers' living things concept: A microgenetic analysis of conceptual change in basic biology. *Cognitive Psychology, 49*, 301–332.

Packiam Alloway, T., & Archibald, L. (2011). Working memory in development: Links with learning between typical and atypical populations. In P. Barrouillet & V. Gaillard (Eds.), *Cognitive development and working memory: A dialogue between neo-piagetian theories and cognitive approaches* (pp. 233–261). Hove: Psychology Press.

Piaget, J. (1929/1973). *The child's conception of the world* (J. Tomlinson & A. Tomlinson, Trans.). St. Albans: Granada.

Pope, M. L., & Denicolo, P. (1986). Intuitive theories – A researcher's dilemma: Some practical methodological implications. *British Educational Research Journal, 12*(2), 153–166.

Smith, J. P., diSessa, A. A., & Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *The Journal of the Learning Sciences, 3*(2), 115–163.

Strauss, A., & Corbin, J. (1998). *Basics of qualitative research: Techniques and procedures for developing grounded theory* (2nd ed.). Thousand Oaks: Sage.

Swanson, H. L. (2011). The influence of working memory growth on reading and math performance in children with math and/or reading disabilities. In P. Barrouillet & V. Gaillard (Eds.), *Cognitive development and working memory: A dialogue between neo-piagetian theories and cognitive approaches* (pp. 203–231). Hove: Psychology Press.

Taber, K. S. (1998). An alternative conceptual framework from chemistry education. *International Journal of Science Education, 20*(5), 597–608.

Taber, K. S. (2000). Case Studies and generalisability – Grounded theory and research in science education. *International Journal of Science Education, 22*(5), 469–487.

Taber, K. S. (2001a). The mismatch between assumed prior knowledge and the learner's conceptions: A typology of learning impediments. *Educational Studies, 27*(2), 159–171.

Taber, K. S. (2001b). Shifting sands: A case study of conceptual development as competition between alternative conceptions. *International Journal of Science Education, 23*(7), 731–753.

Taber, K. S. (2003). The atom in the chemistry curriculum: Fundamental concept, teaching model or epistemological obstacle? *Foundations of Chemistry, 5*(1), 43–84.

Taber, K. S. (2005). Learning quanta: Barriers to stimulating transitions in student understanding of orbital ideas. *Science Education, 89*(1), 94–116.

Taber, K. S. (2009a). Building theory from data: Grounded theory. In E. Wilson (Ed.), *School-based research: A guide for education students* (pp. 216–229). London: Sage.

Taber, K. S. (2009b). *Progressing science education: Constructing the scientific research programme into the contingent nature of learning science*. Dordrecht: Springer.

Taber, K. S. (2013). Revisiting the chemistry triplet: Drawing upon the nature of chemical knowledge and the psychological of learning to inform chemistry education. *Chemistry Education Research and Practice, 14*(2), 156–168. doi:10.1039/C3RP00012E.

Taber, K. S., & Tan, K. C. D. (2011). The insidious nature of 'hard core' alternative conceptions: Implications for the constructivist research programme of patterns in high school students' and pre-service teachers' thinking about ionisation energy. *International Journal of Science Education, 33*(2), 259–297. doi:10.1080/09500691003709880.

Taber, K. S., & Watts, M. (1996). The secret life of the chemical bond: Students' anthropomorphic and animistic references to bonding. *International Journal of Science Education, 18*(5), 557–568.

Talanquer, V. (2007). Explanations and teleology in chemistry education. *International Journal of Science Education, 29*(7), 853–870.

Zohar, A., & Ginossar, S. (1998). Lifting the taboo regarding teleology and anthropomorphism in biology education – Heretical suggestions. *Science Education, 82*(6), 679–697. doi:10.1002/(sici)1098-237x(199811)82:6<679::aid-sce3>3.0.co;2-e.

Part V
Chemical Structure and Bonding

Teaching and Learning of the Chemical Bonding Concept: Problems and Some Pedagogical Issues and Recommendations

Tami Levy Nahum, Rachel Mamlok-Naaman, and Avi Hofstein

Introduction: Rationale for Teaching the Chemical Bonding Concept

Chemical bonding is undoubtedly one of the key concepts in chemistry and one of the most fundamental. It is also one of the areas in the physical sciences where understanding is developed through diverse models—which are in turn built on a range of physical principles—and where students are expected to interpret a disparate range of symbolic representations of chemical bonds (Taber and Coll 2002). The concepts associated with *chemical bonding and structure,* such as covalent bonds, molecules, ions, giant lattices, and hydrogen bonds, are highly abstract. Thus, in order to fully understand these concepts, students must be familiar with mathematical and physical concepts and laws that are associated with the key bonding concepts, such as orbitals, electronegativity, electron repulsion, polarity, and Coulomb's law. In addition, learning about chemical bonding enables students to make predictions and give explanations about physical and chemical properties of substances. Good explanations of atoms, molecules, ions, bonds, and other atomic components are available to help systematize the available chemical knowledge. In each of the following examples of high-school/college level chemistry explanations, material behavior that can be directly investigated is explained in terms of theoretical entities that are part of a conceptual "toolkit":

- Copper conducts electricity because it has metallic bonding with delocalized electrons.
- Diamonds have a high melting temperature because their atoms are strongly bound into a lattice by covalent bonds.

T. Levy Nahum • R. Mamlok-Naaman • A. Hofstein (✉)
Department of Science Teaching, The Weizmann Institute of Science, Rehovot, 76100, Israel
e-mail: avi.hofstein@weizmann.ac.il

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_18,

- Sodium chloride is soluble in water, but not in benzene, because the crystal is held together by strong ionic bonds, but the ions are also able to form bonds with water molecules when hydrated.
- Water evaporates readily because it comprises small covalent molecules.
- Water expands upon freezing because it forms a lattice of hydrogen-bonded molecules.
- A stream of water can be deflected by a charged rod because the molecules have a dipole moment owing to the polar bonds.

In each of these cases, the phenomenon to be explained is something that can be directly demonstrated on the bench (e.g., copper conducts electricity), and the explanation refers to entities that are discussed *as if* real objects (e.g., metallic bonding and delocalized electrons), but which are also theoretical constructs such as the types of bonds between atoms.

The notion of chemical bonding is thus part of an extensive *explanatory framework* that chemists use to make sense of molecular-scale phenomena in terms of a conjectured submicroscopic level of material structure. According to Treagust and Harrison (2000), when crafting explanations, scientists, teachers, and students are not free to use just any sort of explanation to depict a concept; acceptable explanations need to agree with the scientific consensus on the subject, be appropriate for the context, and the target audience, and show holistic agreement. A key feature of models that represent material structures is that matter is not considered to be homogenous and continuous, but rather, at a small enough scale, it comprises myriad components that are considered to be the fundamental particles from which macroscopic structures are built.

Particles at the submicroscopic level—atoms, ions, electrons, and molecules—are unlike more familiar particles such as salt or sugar grains. These particles of the molecular world are fuzzy packets of fields without surfaces or definitive volumes, which extend indefinitely and which can often interpenetrate each other. Using the term “particles” can mislead learners. They are something else—someone commonly called them “quanticles” (Taber 2002b) to emphasize this distinction.

Since chemists understand substances in terms of clusters of submicroscopic particles, the *chemical bonds* between those particles can be used to explain many of the chemical and physical properties of substances as well as chemical phenomena (Hurst 2002; Levy Nahum et al. 2004). A thorough appreciation of its nature and characteristics is essential for understanding almost every other topic in chemistry, such as carbon compounds, proteins, polymers, acids and bases, chemical thermodynamics, proteins, carbohydrates, and polymers (Fensham 1975; Gillespie 1997; Hurst 2002; Levy Nahum et al. 2004). Gillespie (1997), in his essay entitled *Great ideas in chemistry*, considered chemical bonding (i.e., what holds atoms together in molecules and crystals) as one of the six most important key concepts that should be included in every high-school and introductory college chemistry course. In addition, the concept is very much related to understanding many important and fundamental biological aspects such as molecular biology (e.g., DNA and RNA—i.e., nucleic acids). However, based on the literature, *bonding* is considered by teachers, students, and chemists to be a very complicated concept (Gabel 1996; Levy Nahum et al. 2007; Robinson 2003; Taber 1998, 2001a, 2002a; Tsaparlis 1997).

This chapter is targeted at 10–12th-grade (upper secondary school) students. Thus, it mainly focuses on the nature of the "*chemical bond*," assuming that students at this stage have already learned about the periodic table, the particulate nature of matter, elements, compounds, and other basic concepts that are usually taught in chemistry in lower secondary school.

Concepts and Alternative Conceptions: Learning and Teaching the Bonding Concept

General Overview

Much has been said to indicate that learning specific concepts is very much at the heart of learning chemistry. Concepts such as bonding, structure, the reaction rate, and internal energy apply to all chemical systems (Fensham 1975). The comprehension of these concepts has implications regarding understanding the whole chemical process, mainly chemical reactions and chemical properties of substances. Chemical reactions involve the breaking and forming of chemical bonds (Taber and Coll 2002). Therefore, *chemical bonding* is a key concept in chemistry.

As human beings grow and learn to cope with the process of living in the world, they use increasingly more generalizations. A concept, as it is used in education, means a generalization of one sort or another. It is used for several levels of generalization, but all its uses share this characteristic. Without concepts we could not begin to learn chemistry. But conceptualizing is a process of filtering reality, and we need to remember this, at all stages of learning chemistry (Fensham 1975).

Students tend to build themselves alternative conceptions and mental models. According to Taber (2001a), most alternative conceptions in chemistry do not derive from the learner's unschooled world experience. In chemistry, as opposed to biology or physics, the frameworks available for making sense of abstract notions such as molecular geometry or lattice structure are derived only from the learners' understanding of prior science teaching. So how are they derived? Students' alternative conceptions, which are considered to largely stem from the way they have been taught, have been labeled as pedagogic learning impediments (Taber 2001b). The failure to represent the reactant molecules or lattice structures under investigation is a simplification, which encourages students to develop alternative conceptions (Taber and Coll 2002).

The literature contains many examples of students' misconceptions in chemistry, such as the belief that atoms in a metal are hard, but those in liquids are soft (Harrison and Treagust 1996). According to Ben-Zvi et al. (1986), many students do not distinguish between the properties of a substance and the properties assigned to a single, isolated atom. Students believe that the "particles" of a substance, called atoms or molecules, are very small portions of a "continuous" substance. It is suggested that any misconceptions and alternative conceptions that students harbor about the fundamental concepts of atoms and molecules will impede further learning (Griffiths and Preston 1992; Harrison and Treagust 2000).

The Chemical Bond: Pedagogy, Conceptualization, and Misconceptions

Taber (1995, 1998, 2001a, 2002a) conducted an intensive research study on students' misconceptions and learning impediments; this was more recently reviewed by Levy Nahum et al. (2010) regarding the chemical bond concepts. These studies explored various difficulties that students had encountered. Taber (1995), for example, suggested that in further learning, both dichotomies give way to continua. The elements may be categorized according to an electronegativity scale, and bonding may be polar, although most compounds may still exhibit bonding of a type similar to the ionic or covalent model. In this way, essentially covalent compounds will exhibit some ionic characteristics when the electronegativity differs between the elements. Ions may be polarized so that ionic compounds can exhibit some covalent characteristics. Taber and Coll (2002) suggested that bonding may be an intermediate state between covalent and ionic bonds. From a scientific point of view, most materials have bonding that cannot be considered as "purely" covalent or ionic (or metallic). In most materials, the bonding may be best described as intermediate, with varying degrees of covalent and ionic (and metallic) characteristics. The notion of bond polarity indicates that the covalent-ionic dimension should be seen as a continuum, and not as a dichotomy. Gillespie (1997) claimed that "*Electrostatic forces are the only important forces in chemistry*" (p. 862).

Taber and Coll (2002) argued that although electrical forces cannot be used to explain all aspects of chemical bonding, they do provide a comprehensive basis for better understanding bonding phenomena. Thus, an authentic teaching model that is used to introduce a simplified version of chemical bonding should be based on the effect of electrical forces. Taber (2002a) considered, as an example, the term *covalent bond*; he feels that most students entering secondary school do not know what it means. As they progress through school, encountering introductory and more advanced college chemistry, they construct a meaning as they learn the term in a range of contexts. According to Taber (2002a):

> A young student who has just learnt the term of a covalent bond in a very limited context does not share the same set of meanings for the term as teachers. This is not a case of the teacher being right and the student wrong, but of them having a different concept of covalent bond. The teacher and the student use the same word, but…the teacher's meaning is not only extended, it is more sophisticated, more subtle, and more deeply integrated into a framework of chemical ideas. (p. 56)

Finally, students do not possess the rich meaning of the term, as teachers do. In fact, there is a gap between students and their teachers concerning students' understanding of these concepts, as well as in dealing with tasks associated with the term. For the teacher, the task is a routine exercise, but for the students, it is a novel problem. It is suggested that the difference between an exercise and a problem results from differences in the level of familiarity with similar tasks that the individual brings to a given task (Bodner and Domin 1998).

According to Erduran (2003), a lack of effective communication between students and teachers can lead to a mismatch between what is taught and what is learned. In the context of science lessons, symmetry between the nature of teachers' understanding of a particular science topic and students' ideas regarding this topic is critical, because such a match illustrates what scientific knowledge is being taught and learned in the classroom.

One way that teachers and textbooks simplify the physical and chemical concept is by using anthropomorphic explanations. For example, in his research, Taber (1998) showed that 10th-grade students commonly adopt as an explanatory principle the notion that atoms "want" to have "octets" or "full outer shells," and that chemical processes often take place so that atoms can achieve this. Some school textbooks even incorrectly refer to eight electrons in the third or higher shells as a full shell.

Taber and Coll (2002) suggested that students do not learn by the "octet framework," which may lead to learning impediments. The existence of bonding, which does not lead to atoms having full electron shells, is consequently something mysterious to many students. Moreover, students may have difficulty accepting anything that is not clearly explicable in "octet" terms as being a chemical bond. Hence, hydrogen bonding and van der Waals forces cannot be readily fitted into such a scheme, and the difference between intermolecular and intramolecular bonding is not clear to many students.

External Factors that Might Cause Learning Difficulties and Misconceptions in Learning (and Teaching) the Chemical Bonding Concept

The literature indicates several external factors that might cause learning impediments regarding the concept of chemical bonds. Stinner (1995) and Sutton (1996), for example, claimed that analysis of current textbooks is of pivotal importance because it constitutes the most widely and frequently used teaching aids at all educational levels. Some analyses of science textbooks have revealed that they tend to present science as a collection of true or complete facts and as generalizations and mathematical formulations, as if the material has been "read directly from nature." Curriculum developers, and therefore teachers, use as many accurate and precise definitions as possible.

In many chemistry textbooks, elements are conveniently classified as metals or nonmetals (with a few semimetals perhaps mentioned). Often this dichotomy among elements leads to a dichotomous classification of bonding in compounds: *covalent* being between nonmetallic elements and *ionic* being between a metal and a nonmetal.

In her research, Yifrach (1999) claimed that the way textbooks and teachers present the classification of chemical bonds, as if everything is very simple and clear (e.g., hydrogen and covalent bonds), is deluding and misleading. This is not the nature of science. According to a scientist's view, one of the most important skills is the ability to classify intelligently. Thus, Yifrach suggests teaching students to classify initially by themselves in order to expand their understanding and to give them an opportunity to perceive the concepts from different points of view. In this way, the students can sharpen their thinking abilities and better understand the relations between contents, skills, and the scientific process. In considering students' learning difficulties such as those previously discussed, it is not helpful to simply consider the representations of scientific knowledge prescribed in the curriculum as being "correct" or "true," and alternative ideas presented by students as simply being "incorrect" or "false" (Gilbert et al. 1982; Kind 2009). Rather, when considering understanding the concept of chemical bonding, it is important to recognize that science curriculum comprises a set of models intended to provide an authentic representation of the models used by scientists, at a level accessible to learners (Gilbert 2004). This complicates judging the correctness of students' conceptions, and both the nature of the scientific models and the way the topic is taught contribute to students' difficulties in learning this topic.

There are several reasons for dissatisfaction within the chemistry teaching community regarding the current teaching and learning of this concept. We will refer to two main components based on the literature: (1) the traditional *pedagogical approach*, as it appears mainly in many chemistry textbooks worldwide, and (2) the *assessment* methods used worldwide (high-stakes testing). For example, in Israel, students are examined at the end of 12th grade for the Israeli *matriculation examination* (ME) (which are final examinations administered centrally by the Ministry of Education). These examinations influence teachers' instruction and students' learning regarding the *bonding* concept, since, unfortunately, the teachers' main objective is in preparing their students for the ME questions and answers, leading to superficial teaching that results in misconceptions and pseudo-conceptions (Levy Nahum et al. 2004, 2007).

Gilbert et al. (1982) pointed out the importance of avoiding confusion between what is commonly called "children's science" and "scientist's science," or for that matter "teacher's science." Certainly in terms of school science teaching, it would often be quite inappropriate to consider the current "state-of-the-art" scientific models as suitable target knowledge for governing the planning of teaching and the evaluation of student learning. Rather, there is at least a two-stage process of transformation between "scientific knowledge" and the learning material set out for students to learn in classes.

The first stage of transformation generally occurs at a system-wide level, beyond particular schools or classrooms—at least in educational systems where there is a prescribed curriculum or a set of reference "standards." In this process, the models of science inform the development of curricula models: representations of scientific knowledge for a particular age range considered to be suitable for teaching and learning. These curricula models are intended to authentically represent the science, but at a suitable level of simplification. This process of curricula model development is usually undertaken by committees, which are often dominated by educators who do not themselves develop and apply the scientific models in their professional work. There is inevitably a process of interpretation, therefore, which may lead to aspects of the scientific models being misconceived and distorted.

Gillespie (1997) provided an example of the type of argument that reflects the development of curriculum in science. He suggested that chemical bonding be treated in introductory general chemistry courses (at an undergraduate level). Some specific concepts are as follows: all chemical bonds are formed by electrostatic attractions between positively charged cores and negatively charged valence electrons. Electrostatic forces are the only important force in chemistry. Bonds are not formed by the overlap of orbitals, as we frequently read; this is just a model—admittedly a very useful one and essential for the chemistry major, but we do not think it is essential for students at the introductory level.

An Attempt to Overcome Some of the Conceptual Problems: The Israeli Longitudinal Project

Introduction

In this section of the chapter, we will describe a longitudinal project in which the main goal was to diagnose the sources and nature of learning difficulties related to the bonding concept and to develop a model for learning and instruction to overcome these learning difficulties and misconceptions. The project will be described in alignment with the three consequential phases that were included, namely, the diagnostic phase aimed at finding the sources that lead to difficulties and misconceptions; the phase in which development of ideas, models, and pedagogy for a new approach (model) was conducted; and finally, the implementation phase in which the new teaching model was tried in one high school (a case study).

The 1st Phase: Diagnostic Research Aimed at Identifying Problems Related to Teaching the Chemical Bonding *Concept*

As mentioned before, one of the key ways of diagnosing difficulties in learning the "chemical bonding concept" is by examining the matriculation examinations (ME). The findings from our diagnostic research study mentioned previously (Levy Nahum et al. 2004) led us to assume that the current method of evaluating students has a critical impact on the teaching and learning of the bonding concept, i.e., the teachers' main objective is to prepare their students for the examination, and this is done by providing them with precise definitions and a set of rigid rules, which inevitably leads to superficial teaching and meaningless learning. The analysis suggests that the general approach to the curriculum, along with the current system of assessment, causes students to memorize key science education phrases (declarations) and to explain facts by using declarative knowledge, resulting in students lacking a fundamental understanding of this concept.

The ME-type questions (the common questions) and the corresponding "acceptable answers" are problematic due to the following factors: (a) they are not always aligned with the views of chemists and (b) they are often based on memorization and thus do not foster students' understanding. Two examples of common questions and the answers that are acceptable to the Ministry of Education are as follows:

(a) A question and the corresponding answer: which are not aligned with currently studied science: *Which material has a higher melting point—*$BaCl_2$ *or C (diamond)? Justify your answer.*

The acceptable answer to this question: *The melting point of C (diamond) is higher than the melting point of* $BaCl_2$ *because the covalent bonds between the carbon atoms in the diamond are stronger than the ionic bonds in* $BaCl_2$.

For many years, chemists in Israel have argued that this type of question is not relevant to ask since the students are required to compare the melting point of two different structures of giant lattices, and students cannot use qualitative understanding in order to answer it (Naaman,14 November 2002, personal communication). Thus, their answer to such questions can be based only on memorization of nonscientific overgeneralizations with no understanding of bond strength.

(b) A question and the corresponding answer, which are based on *rote memorization* and thus do not foster students' scientific thinking: *The boiling point of* Cl_2O *is lower than the boiling point of* H_2O_2. *Explain this fact.*

The acceptable answer to this question: *The boiling point of* Cl_2O *is lower than the boiling point of* H_2O_2 *because the hydrogen bonds between the* H_2O_2 *molecules are stronger than the van der Waals interactions between the* Cl_2O *molecules.*

It is suggested that students can answer this type of question and can achieve high grades, but use of the correct terms cannot guarantee that they will understand the relevant concepts (such as hydrogen bonds or van der Waals interactions). According to Henderleiter et al. (2001), students apparently rely on rote memorization to determine which elements could be involved in hydrogen bonding. Although rote memorization of some facts is critical, often students memorize a list or a pattern but are not able to fully comprehend it. Based on these studies and supported by a study conducted previously by Glazer et al. (1999), we can conclude that in general, common questions cannot serve as a diagnostic tool for evaluating students' understanding. Although it appears that the examination does reveal students' use of alternative conceptions, it *does not* indicate that students understand the underlying concepts because they can often provide the correct answer just by using the right terminology. These conclusions are supported by an extensive research effort in science education demonstrating that success in solving algorithmic exercises does not necessarily indicate understanding scientific concepts (Lythcott 1990; Salloum and Abd-El-Khalick 2004; Taagepera et al. 2002; Teichert and Stacy 2002; Vinner 1997). For example, Lythcott claimed that if correct solutions to problems yield high grades but do not guarantee that the relevant chemistry concepts have been understood, then one must seriously question what is being assessed.

Consequently, the problem is not always the problem of *misconceptions*; rather, students often answer questions by using terms used by their teachers but do not actually understand these concepts. According to Vinner (1997), whenever students use the right terms in the right context with no conceptual thinking or scientific understanding, they use what he calls *pseudo-conceptions*.

Based on previous studies, three main categories of students' difficulties regarding the bonding concept were identified. These include the following:

- Students confuse intramolecular bonds and intermolecular bonds (Taagepera et al. 2002).
- Students tend to overgeneralize and use rote memorization instead of scientific explanations (Taber and Watts 2000).
- Students often use pseudo-conceptions; they use the right terms and concepts but do not understand their meaning or their conceptual relevance (Vinner 1997).

The common exam questions do not adequately evaluate students' understanding. Perkins (1998) claimed that *understanding* means being able to carry out a variety of *performances*, which shows one's understanding of a concept, and at the same time, advances it. He calls such performances *understanding performances*. Understanding students' performances must consider beyond what they already know. Many student performances are too routine to be considered as understanding, such as deciding whether a statement is true or false and solving standard arithmetic exercises. Building on the work of Perkins, Reiser et al. (2003) suggested using the notion *learning performances* in order to illustrate the understanding that students should possess as a result of the various tasks performed. They claimed that curriculum developers must first determine the key-learning goals, namely, the "big ideas" and the abilities that students should acquire before constructing materials and assessments. They argued that to assess whether students learned the key concepts, developers need to (1) translate the declarative statement of understanding into a set of observable cognitive performances and (2) be explicit about what kinds of cognitive performances are considered as evidence for adequate understanding.

We can conclude that the common questions are not based on specific key-learning goals and thus do not foster the development of understanding aligned with learning performances. According to Birenboum (1997) and Dori (2003), this system of assessment detracts from teachers' efforts to ensure meaningful learning and developing students' higher-level thinking abilities. In light of this, we recommend abandoning the current pattern of questioning and instead, assessing students' argumentation and thinking skills, which examine their learning performances. According to Pellegrino et al. (2001), alignment of assessment, curriculum, and instruction with well-specified key-learning goals is essential for students' meaningful learning.

The 2nd Phase: Developing a Model for Teaching the Chemical Bonding Concept

The Methodology Used for Developing the New Teaching and Learning Model

Based on long-term collaboration between prominent scientists, researchers in chemistry education, and expert teachers, an innovative program aimed at teaching the chemical bonding concept, which follows a holistic approach to curriculum design was developed and implemented in 11th-grade chemistry classes in Israel (Levy Nahum et al. 2007). The main goal of the 2nd phase of the current project was to develop a new teaching approach for the *bonding* concept by deconstructing the traditional approach and constructing a reformed approach aligned with the scientists' views. Our idea was to explore the development and implementation of a more scientific and effective teaching approach in order to improve students' understanding of the concept and at the same time to maintain (as much as possible) a valid scientific approach.

As previously mentioned, in order to achieve this rather demanding goal, we used different groups of participants (leading chemistry teachers, scientists, and chemistry educators) and several methods of developmental activities such as a scientific symposium, a focus group (Morgan 1997), and in-depth interviews (for more details, see Table 1).

As shown in Table 1, several activities were employed, along with suitable tools; we used a triangulation method in order to collect relevant and valid data. These, together with the information that was gathered throughout a 14-year period (the matriculation examination results enabled us to construct the new approach to learning the bonding model).

The Bottom-Up Approach for the New Model

The general approach used for the new model for teaching the chemical bonding topic relies on basic concepts and ideas such as Coulombic forces and energy at the atomic level to build a coherent and consistent perspective for dealing with all types of chemical bonds. As described by Levy Nahum et al. (2008, p. 1680): "It is possible to show how this diversity [of bond types] arises from a small number of fundamental principles instead of presenting it as a large number of disparate concepts." The framework proposed by Levy Nahum et al. (2008) (see Fig. 1) introduces the elemental principles of an isolated atom (stage 1); this is followed by discussions of general principles of chemical bonding between two atoms (stage 2); then, the general principles are used to present the different traditional categories of chemical bonding as extreme cases of various continuum scales (stage 3). Equipped with this knowledge, students can then construct a coherent understanding of different molecular structures (stage 4) and properties (stage 5).

Table 1 The research participants and the main data sources

Participants	The participants' role	Data sources from the activities
Senior chemists and senior chemistry educators ($N = 10$)	To provide us with their *scientific perceptions and explanations* regarding the concept *chemical bonding* and their views regarding the *pedagogical approach* for teaching this topic	Tapes and notes from ten in-depth interviews with the scientists
A senior chemical physicist (from the ten above)	To provide 20 chemistry leading-teachers with a scientific symposium	Tapes and notes from the symposium
Experts in chemistry teaching ($N = 10$; 10 out of the 20 that participated in the symposium). These experts are chemistry leading-teachers who are also curriculum developers and/or lecturers of undergraduate chemistry students and/or researchers in chemistry teaching	To provide us with the views of experts in chemistry teaching regarding (1) The problematic ME questions and answers (2) The problems regarding the current pedagogical approach (3) The scientists' views of *chemical bonding* Through brainstorming and focused discussions, we formulated "big ideas" (*learning goals*) and constructed a new approach for teaching the *chemical bonding* concept including developing new assessment tasks (based on a set of *learning performances*)	Tapes and notes from a focus group, which was conducted with these experts in a workshop during the academic year 2005 (six meetings, 4 h each)
11th-grade chemistry students ($N = 77$)	In order to examine new assessment tasks (which were developed during the workshop) compared to the traditional ME questions, we administered an achievement test to 11th-grade chemistry students who studied the traditional program	Results from the achievement test

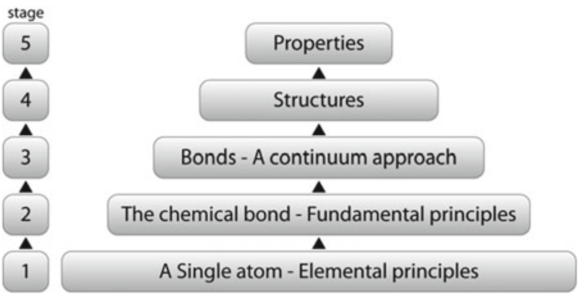


Fig. 1 A schematic illustration of a new "bottom-up" framework for the teaching chemical bonding concept

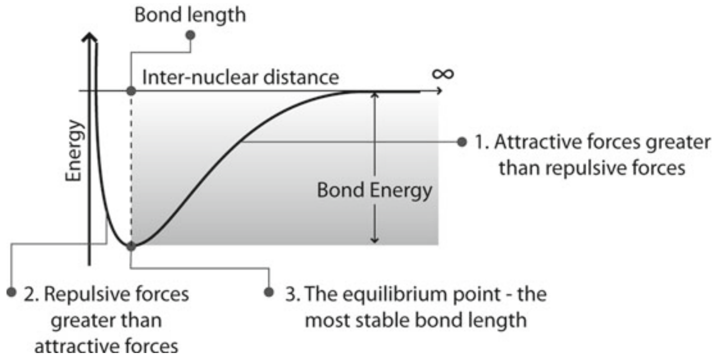


Fig. 2 A schematic energy curve for any two atoms that interact

The primary purpose of the second stage is to provide a qualitative description that is conceptually consistent with quantum mechanics but provides a very clear, intuitive answer to the question that puzzles many students, “What *really* causes atoms to interact and form a chemical bond?” In order to provide evidence to students that there is nothing “mysterious” about chemical bond formation, this stage begins by introducing the concepts of *energy* and *force* and the interrelation between them. The understanding that nuclei are held together because of a nucleus–electron attraction, which is a consequence of Coulomb’s law, is the first step toward achieving a rational view of chemistry that is *not* based on rules of thumb, anthropomorphic concepts, etc. Note that this does not mean that these tools are useless. However, it is suggested that they do not provide a clear scientific explanation, and, thus, they are insufficient if we aim at learning with understanding. A crucial concept is that *stability*, in general, is obtained by minimizing energy. The above principles are best explained by considering the energy curve for any two initially isolated atoms that interact (approach each other) (Fig. 2).

Figure 2 shows that if there is any net gain of energy from bringing atoms together, there will be a region where, even though nuclei generally repel each other because they are both positive, there will be a net attraction because the nucleus–electron attraction acts as “glue” for the nuclei. If the atoms are close enough, there will be a net repulsion. The “equilibrium distance,” namely, the bond length, is then simply the special point at which net attraction exactly offsets net repulsion, and the bond energy is the net gain in energy obtained at this point, with respect to the well-separated limit of atoms. This is a stable equilibrium point because both increasing and decreasing the interatomic distance requires energy. Once this is understood, *all* chemical bonds, of any type, can be rationalized in terms of bond dissociation energy, and interatomic distances (i.e., *bond lengths*) reflect positions where there is no net force on the nuclei, i.e., attraction balances repulsion.

Importantly, Fig. 2 is *general*. It describes the relation between energy and the internuclear distance for the H_2 dimer; it also describes the Na_2 dimer, the LiCl dimer, or even the He_2 dimer. Obviously, there is very much that separates H_2 and He_2.

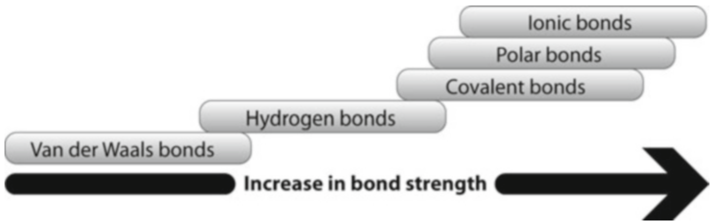


Fig. 3 A schematic continuous scale of bond strength

One of the key goals of the proposed framework is to emphasize that a continuum scale exists between extreme cases of qualitatively different bonding scenarios. After the common denominator of all bonds, in stage 2, has been understood, some distinct bonding categories can now be rationalized, as shown in Fig. 3. An example of a chemical bond in a diatomic molecule may be most useful because of the emphasis only on one bonding entity. In this context, the concept of electronegativity can be introduced, naturally, as one way of quantifying the covalence/ionicity balance. This continuum follows Pauling (1967), who recognized that bonds between unlike atoms typically have greater bond energy than that of the average of the corresponding homo-atomic bonds. However, bond strength is not *only* a function of the degree of ionicity—it is also a function of atomic size and other factors. Similar arguments are also given and discussed in relation to hydrogen and van der Waals interactions (for more details, see Levy Nahum et al. 2008).

Phase 3: Implementing the Approach in an Educational System

There is no doubt that one of the most important phases in the curricular process is the phase in which teachers implement a new approach in their classroom. Clearly, the way teachers translate (and adopt) a certain instructional unit or a model in their school will determine its related educational effectiveness. This in return will affect students' understanding of concepts. The data sources we used in order to learn about students' understanding consisted of audiotapes and notes mainly from a *case study* of one class (observations, 35 h, including audiotapes and notes) and from the special ME questionnaires, as follows:

- The case study: the observed experimental teacher—conversations, comments, problems, and recommendations
- The case study: experimental students ($N=40$)—questionnaires (pre–post), comments during the lessons, and in-depth interviews (experimental students ($N=7$)) with written comments and figures
- Preliminary results from the special ME questionnaires

Results Obtained from the Experimental Teacher

In the academic year 2005, the researcher spent two and a half months in one of the experimental classes. All together, a total of 35 lessons were audio-recorded and notes were taken. Preliminary findings are reported in the following section. After the lessons, the teacher discussed with the researcher several aspects regarding the lesson (such as "surprises," difficulties, and scientific questions). After 2 weeks (six lessons) of teaching, the teacher claimed:

> During the summer course I thought that the energy curve and concepts such as orbitals and the equilibrium point would be difficult for my students to understand. But I was wrong. They understood intuitively the fact that the chemical bond is most stable when the attraction and repulsion forces are "equal."

Results Obtained from the Students

The students ($N = 40$) who studied the *bonding* concept using the new approach were asked to complete a short questionnaire before and after the unit was implemented. They were asked to explain in their own words the *chemical bonding* concept and to detail which principles and key concepts are required to explain this concept. These students studied chemical bonding traditionally, at the end of 10th grade. On the *pretest*, 26 students defined a chemical bond as a "bond"/"connection" between atoms; 12 students indicated notions such as molecules, mixtures, and elements, and 11 students indicated the concept of attraction forces as key concepts for explaining bonds. However, on the *posttest*, 19 students defined a chemical bond as an attraction between negative and positive electric charges, 5 out of the 19 referred to the energy curve and mentioned the decreased energy and the equilibrium point; 25 students indicated key concepts such as attraction and repulsion forces, bond energy, bond length, orbitals, electronegativity, and *Coulomb's law* as essential for explaining bonds.

In addition, seven students (two high-achievers, three average-level students, and two low-achievers) were interviewed by the researcher, after implementing the unit, regarding their understanding of the key issues that underlie the *chemical bonding* concept. As mentioned in our previous studies (Levy Nahum et al. 2004, 2007), several students who gave the correct answer for the ME question regarding the H-bond drew lines between two hydrogen atoms, or between two oxygen atoms, or between hydrogen and oxygen in a single water molecule to indicate the H-bond. However, in the experimental class, all 7 students correctly drew the H-bond that might occur between two water molecules and 6 out of the 7 added the oxygen nonbonding electrons and drew the bond through these electrons. We end this part by quoting two students. These quotes strongly enhanced our faith in our new approach.

> Student 1: *The continuum scale of bonds helped me to understand…last year the teacher said: 'it's one of the two' (covalent/ionic)…*

Student 2: *The difference between the intramolecular and intermolecular bonds in Br_2 molecules is that whereas the intramolecular bond is directional and is a result of an overlap of orbitals, the intermolecular bond (van der Waals) is non-directional and lacks orbital overlap…*

Preliminary Results from the Special Matriculation Examination Questionnaires

At the end of 2006 and 2007, the experimental students were examined by special ME questionnaires that were developed by the developers of the new curriculum. Experimental teachers checked the special ME of their colleagues' students. First, the questions about bonding were chosen by most of the students. According to the teachers, this means that they felt that they had a good understanding of this topic. Second, their average grade was around 80—namely, that the experimental students were not negatively affected by the new program. And finally, and most important, the teachers reported that their students' answers indicated that they had attained a deep understanding of the bonding concept and related principles. For example, their explanations regarding hydrogen bonds included important characteristics such as the role and the position of the nonbonding electrons in the electronegative atom and the specific direction of the bond; they actually drew the nonbonding orbital and drew a line between the three nuclei right through this orbital.

At this stage, we are satisfied with the *preliminary results*. We believe that this approach encourages the teachers and students to think about and to ask relevant scientific questions. In this way, students can acquire a much deeper understanding of the underlying key concepts.

Discussion and Summary

The research project described in this chapter consists of almost all the components of a curricular process, a diagnostic study, followed by curricular development and implementation regarding the teaching of the *bonding* concept. High-school students lack a fundamental understanding of key concepts of chemical bonding. One of the goals of the chemistry teaching community is to develop more effective and scientifically aligned strategies to teach high-school students this key concept.

The traditional pedagogical approach to teaching *chemical bonding and structure* is often overly simplistic and thus is not aligned with the most up-to-date scientific knowledge and models. The problematic approach by which this topic is presented in many chemistry textbooks worldwide has been examined extensively in the last two decades by researchers of chemistry teaching (Ashkenazi and Kosloff 2006; Hurst 2002; Justi and Gilbert 2002; Taber 1998; Atzmon 1991). The traditional approach, as it appears in many textbooks, is oversimplified and thus leads to overgeneralizations as well as a lack of scientific tools that could promote students' understanding. Taagepera et al. (2002) claimed that effective comprehension and thinking require a coherent understanding of the *organizing principles*. Hurst (2002) concluded his paper with the suggestion that *bonding* theory and related concepts need to be taught in a *uniform* manner.

The concept *chemical bonding* was designed to fulfill these needs. In the first stage of the study (Levy Nahum et al. 2004), we used several methods and sources in order to explore the problem, and based on our findings, we concluded that students display a shallow understanding of *chemical bonding* not only because this topic has intrinsic complexities but also as a result of external *misleading factors* concerning the traditional approach used for teaching the *bonding* concept.

In fact, as we described, based on our paper (Levy Nahum et al. 2008), and as we previously mentioned, the problem lies in the current textbooks; so in a retro-perspective view, we could have started by analyzing chemistry textbooks and, based on our conclusions, develop a new framework for a new unit. However, we started using a problematic assessment approach, and the process it generated. This provided us with rationalization and a deep foundation for a meaningful and detailed analysis and insights regarding the misleading factors. These factors are detailed in Levy Nahum (2007) and in Levy Nahum et al. (2004) and supported by studies conducted worldwide. Thus, we recommended making a real change in the traditional approach used for teaching this topic.

Based on the findings of the previous phase, we proposed a plan to eliminate the addressed problems. In the second stage (Levy Nahum et al. 2007), we described a collaborative development process with leading-teachers, researchers in chemistry teaching, and senior chemists. We referred to all the problematic aspects of the traditional approach and obtained a consensus regarding the organizing principles and the key concepts of this topic based on a partnership between senior scientists and expert teachers, which follows a holistic approach to the curriculum. During this process, a conceptual framework was constructed for re-characterizing the *chemical bonding* concept.

It should be emphasized that the chemistry teachers were deeply involved in the curricular process; they cooperated with the developers and provided valuable feedback and insights throughout the process. Their contribution to the design of the new approach, in all its stages, was enormous. Thus, we highly recommend that any curricular development be conducted with the teachers' and scientists collaborations.

References

Ashkenazi, G., & Kosloff, R. (2006). The uncertainty principle and covalent bonding. *The Chemical Educator, 11*, 66–76.

Atzmon, A. (1991). *Natural science curriculum as designer of the image of science using rhetorical patterns within the socio-political system*. Unpublished doctoral dissertation, Hebrew University, Jerusalem (in Hebrew).

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education, 63*, 64–66.

Birenboum, M. (1997). *Alternatives in assessment*. Tel-Aviv: Ramot (in Hebrew).
Bodner, G., & Domin, D. (1998). *Mental models: The role of representations in problem solving in chemistry*. In International Council for Association in Science Education, Summer Symposium, Proceedings, Hong Kong.
Dori, Y. J. (2003). From nationwide standardized testing to school-based alternative embedded assessment in Israel: Students' performance in the matriculation 2000 project. *Journal of Research in Science Teaching, 40*, 34–52.
Erduran, S. (2003). Examining the mismatch between pupil and teacher knowledge in acid-base chemistry. *School Science Review, 84*(308), 81–87.
Fensham, P. (1975). Concept formation. In D. J. Daniels (Ed.), *New movements in the study and teaching of chemistry* (pp. 199–217). London: Temple Smith.
Gabel, D. (1996, July). *The complexity of chemistry: Research for teaching in the 21st century*. Paper presented at the 14th International Conference on Chemical Education, Brisbane, Australia.
Gilbert, J. K. (2004). Models and modeling: Routes to more authentic science education. *International Journal of Science and Mathematics Education, 2*, 115–130. doi:10.1007/s10763-004-3186-4.
Gilbert, J. K., Osborne, R. J., & Fensham, P. J. (1982). Children's science and its consequences for teaching. *Science Education, 66*, 623–633.
Gillespie, R. (1997). The great ideas of chemistry. *Journal of Chemical Education, 74*, 862–864.
Glazer, N., Ben-Zvi, R., & Hofstein, A. (1999, March). *The gap between factual knowledge and conceptual understanding in learning the concept "chemical bonding"*. Paper presented at the annual meeting of the National Association for Research in Science Teaching, Boston.
Griffiths, A., & Preston, K. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*, 611–628.
Harrison, A. G., & Treagust, D. F. (1996). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. *Science Education, 80*(5), 509–534.
Harrison, A. G., & Treagust, D. F. (2000). Learning about atoms, molecules, and chemical bonds: A case study of multiple-model use in grade 11 chemistry. *Science Education, 84*, 352–381.
Henderleiter, J., Smart, R., Anderson, J., & Elian, O. (2001). How do organic chemistry students understand and apply hydrogen bonding? *Journal of Chemical Education, 78*, 1126–1130.
Hurst, O. (2002). How we teach molecular structure to freshmen. *Journal of Chemical Education, 79*(6), 763–764.
Justi, R., & Gilbert, J. (2002). Models and modeling in chemical education. In J. K. Gilbert, O. D. Jong, R. Justy, D. F. Treagust, & J. H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 47–68). Dordrecht: Kluwer.
Kind, V. (2009). Pedagogical content knowledge in science education: Perspectives and potential for progress. *Studies in Science Education, 45*, 169–204.
Levy Nahum, T. (2007). *Teaching the concept of chemical bonding in high-school: Developing and implementing a new framework based on the analysis of misleading systemic factors*. Unpublished doctoral dissertation, Weizmann Institute of Science, Rehovot, Israel (In Hebrew).
Levy Nahum, T., Hofstein, A., Mamlok-Naaman, R., & Bar-Dov, Z. (2004). Can final examinations amplify students' misconceptions in chemistry? *Chemistry Education Research and Practice in Europe, 5*(3), 301–325.
Levy Nahum, T., Mamlok-Naaman, R., Hofstein, A., & Krajcik, J. (2007). Developing a new teaching approach for the chemical bonding concept aligned with current scientific and pedagogical knowledge. *Science Education, 91*, 579–603.
Levy Nahum, T., Mamlok-Naaman, R., Hofstein, A., & Kronik, L. (2008). A "bottom-up" framework for teaching chemical bonding. *Journal of Chemical Education, 85*, 1680–1685.
Levy Nahum, T., Mamlok-Naaman, R., Hofstein, A., & Taber, K. (2010). Teaching and learning the concept of chemical bonding. *Studies in Science Education, 46*(2), 179–207. doi:10.1080/03057267.2010.504548.
Lythcott, J. (1990). Problem solving and requisite knowledge of chemistry. *Journal of Chemical Education, 67*, 248–252.

Morgan, D. L. (1997). *Focus group as qualitative research* (2nd ed.). London: Sage.
Pauling, L. (1967). *The nature of the chemical bond, and the structure of molecules and crystals: An introduction to modern structural chemistry* (3rd ed.). Ithaca: Cornell University Press.
Pellegrino, J. W., Chudowsky, N., & Glaser, R. (Eds.). (2001). *Knowing what students know: The science and design of educational assessment*. Washington, DC: National Academy Press.
Perkins, D. (1998). What is understanding? In M. S. Wiske (Ed.), *Teaching for understanding: Linking research with practice*. San Francisco: Jossey-Bass.
Reiser, B., Krajcik, J., Moje, E., & Marx, R. (2003). *Design strategies for developing science instructional materials*. Paper presented at the annual meeting of the National Association of Research in Science Teaching, Philadelphia.
Robinson, W. (2003). Chemistry problem-solving: Symbol, macro, micro, and process aspects. *Journal of Chemical Education, 80*, 978–982.
Salloum, S., & Abd-El-Khalick, F. (2004). Relationships between selective cognitive variables and students' ability to solve chemistry problems. *International Journal of Science Education, 26*(1), 63–84.
Stinner, A. (1995). Science textbooks: Their present role and future form. In S. M. Glynn & R. Duit (Eds.), *Learning science in the schools* (pp. 275–296). Mahwah: Lawrence Erlbaum Associates.
Sutton, C. (1996). Beliefs about science and beliefs about language. *International Journal of Science Education, 18*, 1–18.
Taagepera, M., Arasasingham, R., Potter, F., Soroudi, A., & Lam, G. (2002). Following the development of the bonding concept using knowledge space theory. *Journal of Chemical Education, 79*(6), 756–762.
Taber, K. S. (1995). Development of student understanding: A case study of stability and liability in cognitive structure. *Research in Science and Technological Education, 13*, 89–99.
Taber, K. S. (1998). An alternative conceptual framework from chemistry education. *International Journal of Science Education, 20*, 597–608.
Taber, K. S. (2001a). Building the structural concepts of chemistry: Some considerations from educational research. *Chemistry Education Research and Practice, 2*, 123–158.
Taber, K. S. (2001b). Shifting sands: A case study of conceptual development as competition between alternative conceptions. *International Journal of Science Education, 23*, 731–753.
Taber, K. S. (2002a). *Chemical misconceptions—Prevention, diagnosis and cure: Theoretical background* (Vol. 1). London: Royal Society of Chemistry.
Taber, K. S. (2002b). Conceptualizing quanta: Illuminating the ground state of student understanding of atomic orbitals. *Chemistry Education Research and Practice, 3*, 145–158.
Taber, K. S., & Coll, R. (2002). Bonding. In J. K. Gilbert, O. D. Jong, R. Justy, D. F. Treagust, & J. H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 213–234). Dordrecht: Kluwer.
Taber, K. S., & Watts, M. (2000). Learners' explanations for chemical phenomena. *Chemistry Education Research and Practice in Europe, 1*(3), 329–353.
Teichert, M., & Stacy, A. (2002). Promoting understanding of chemical bonding and spontaneity through student explanation and integration of ideas. *Journal of Research in Science Teaching, 39*(6), 464–496.
Treagust, D. F., & Harrison, A. G. (2000). In search of explanatory frameworks: An analysis of Richard Feynman's lecture 'Atoms in motion'. *International Journal of Science Education, 11*, 1157–1170.
Tsaparlis, G. (1997). Atomic and molecular structure in chemical education. *Journal of Chemical Education, 74*, 922–925.
Vinner, S. (1997). The pseudo-conceptual and the pseudo-analytical thought processes in mathematics learning. *Educational Studies in Mathematics, 34*, 97–129.
Yifrach, M. (1999). *Definition of chemical literacy and assessment of its attainment in high school chemistry*. Unpublished master's thesis, Weizmann Institute of Science, Rehovot (in Hebrew).

A Common Core to Chemical Conceptions: Learners' Conceptions of Chemical Stability, Change and Bonding

Keith S. Taber

Introduction

This chapter discusses learners' thinking about chemistry at the submicroscopic level, that is, when they think about molecules, ions and atoms, and how they interact. Scientists, and in particular chemists, have extensive explanatory schemes relating to aspects of the structure and properties of materials, based upon the theoretical properties and behaviour of conjectured submicroscopic particles. Indeed, in learning chemistry beyond the most introductory level, talk of molecules, ions, electrons and so forth is ubiquitous, and there is a sense in which no one can be considered to understand chemistry as a modern science unless they appreciate at least some of this conceptual framework for the subject.

It is widely accepted that learners develop alternative understandings of scientific topics, and a major strand of science education research for some decades has explored the nature and consequences of learners' thinking for learning of the science presented in the curriculum (Duit 2009). This work has largely been carried out from a constructivist perspective (Gilbert 1995; Glasersfeld 1989; Sjøberg 2010), where it is acknowledged that learning is largely an iterative and contingent process: what we (think we) know today is a major factor in what we can learn tomorrow. The outcomes of this body of research have variously been described in such terms as misconceptions, alternative conceptions, intuitive theories and a range of other descriptors (Gilbert and Watts 1983; Hammer 1996; Pope and Denicolo 1986). Some of this variation in terminology simply reflects researchers' preferences, and some reflects very real differences in the reported status and nature of the ideas (Taber 2009b).

K.S. Taber (✉)
Faculty of Education, University of Cambridge, Cambridge, UK
e-mail: kst24@cam.ac.uk

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_19,

In 1998, the present author published a research report deriving from a doctoral study on ‘Understanding Chemical Bonding’, claiming that learners’ ideas in this area appeared to make up an ‘alternative conceptual framework’, that is a largely coherent theory-like basis for thinking about aspects of chemistry (Taber 1998, 1999a). Although my focal topic was chemical bonding, it was clear that this framework was used to think about related themes such as chemical reactions, chemical stability and ionisation energies. The original research was an in-depth interview-based study with a modest number of ‘advanced level’ students (typically 16–19-year-olds) studying chemistry in a further education college in England. However, following up on the original findings, data has since been collected from more diverse samples of students, including some in different educational contexts, and this has offered evidence suggesting that the original findings were generalisable beyond both the original institution and also the English educational system. This is important, as it suggests that the nature of the thinking uncovered in the original research was not largely due to a particular teaching approach, or a particular curriculum specification, but seems to reflect something more basic about the interaction between learners’ minds and the nature of the models presented in chemistry education.

In this chapter, I will:

- Set out the common alternative conceptual framework and explain how it was derived from the original interview study.
- Explain how this ‘octet’ framework is influential across a range of topics in chemistry and, therefore, supports the development of a spread of ‘misconceptions’.
- Review some of the research suggesting this is a common conceptual framework, used by many students in different educational contexts.
- Briefly review the ways in which learners are believed to develop ‘alternative conceptions’ and suggest two likely sources of this common way of thinking about chemistry:
  - Firstly, that this particular idea is a pedagogic learning impediment – that is, that part of the popularity of this alternative conceptual framework derives from the way chemistry is taught
  - Secondly, that, in part at least, the insidious nature of this way of thinking about chemistry reflects intuitive elements of cognition involved in preconscious thought
- Finally, I will suggest what this research indicates about (a) teaching the submicroscopic concepts of science and (b) potentially fruitful areas for further research.

The structure of the early sections of the chapter is ‘pedagogical’, rather than chronological, because it is believed this offers a better narrative for readers. The section entitled ‘A common alternative explanatory principle adopted by learners to make sense of chemistry’ introduces the key findings from an interview study undertaken with 16–19-year-old college students studying chemistry, concerning how they made sense of the chemical bonding concept (largely based on their prior school learning). In the English context, schooling is compulsory till age 16, and up to this point, students follow a range of subjects. Students who wish to apply for university courses usually then study for two further years at 'Advanced Level', or A Level, selecting a smaller number of subjects. Most of the students in the original interview study were taking A Level Chemistry, alongside two other subjects that were chosen individually.

The following section, 'An alternative framework for thinking about chemical stability, change and bonding', is based upon the same study but considers how the key ideas were applied and extended in a range of topics that students met during their college chemistry course. Then, the section entitled 'Generalisability of the octet alternative conceptual framework' explores other research that suggests that key aspects of the findings deriving from the original study apply to students learning chemistry in a range of contexts (and are not limited, e.g. to English college students). This section includes discussion both of studies carried out by the present author and his colleagues and of completely independent research that has reported similar findings. Some work that clearly predates the present author's studies is included in this section (rather than earlier) to provide a more coherent review.

Given the space limitations of the chapter, only outline details will be given of the contents of studies mentioned here. Readers are referred to the original published studies for details of samples, methodologies used and precise findings. The purpose here is simply to make the case that findings from a range of studies are providing an increasing evidence base for believing that there is a common way of thinking about chemistry that is acquired by students across different educational contexts.

Research reports giving accounts of the thinking of others are necessarily reporting inferences drawing on data that has been interpreted during analysis. Thinking, ideas, conceptions and other mental phenomena are only indirectly available to others through the way we represent our subjective experience (e.g. through speech, gesture, drawings), and must then be interpreted through the cognitive processes of those others for them to make sense of the representations. To aid readability, I have not always made these provisos explicit, but all references to the ideas, thinking, etc. of my informants need to be understood as my reporting my interpretations of the data collected.

A Common Alternative Explanatory Principle Adopted by Learners to Make Sense of Chemistry

The claim made in the 1998 paper was that among the students interviewed for the study, there was an adoption of a common explanatory principle, that chemical processes can be explained at the submicroscopic level in terms of atoms acting to acquire particular electronic configurations. An immediate complication is that students did not all use precisely the same terms but could refer to atoms *filling their shells* or obtaining *octets* of outer electrons, or acquiring *noble gas electronic configurations*. The common feature was that students recognised that certain electronic arrangements had an inherent stability (a reasonable interpretation of teaching), and saw the ability to acquire these arrangements as a sufficient basis for explaining chemical processes (which, as will be explained, forms an inappropriate generalisation).

Some of my informants were very generous with their time, allowing me to explore their ideas in a range of contexts, and as their thinking developed during their Advanced Level Chemistry course. For example, one student (given the assumed name Tajinder) was interviewed over 20 times, often for well over an hour at a time, and provided the basis for a particularly detailed case study (Taber and Watts 1997). From this extensive database, it was possible to report on how Tajinder had demonstrated 'manifold conceptions', in having several alternative ways of thinking about chemical processes. So during his course, Tajinder drew upon three distinct ways of explaining chemical bonding, and these appeared to make up a repertoire of explanatory principles that could be used as the basis of complementary explanations (Taber 2000b). At the start of his course, one particular type of explanation dominated, which I labelled the '*full-shells explanatory principle*', i.e. that bonds formed to allow atoms to obtain full shells. During his course, as he learnt more chemistry, there was a shift and Tajinder increasingly tended to discuss chemistry instead in terms of the electrical interactions between molecules, ions, nuclei, electrons, etc. (Taber 2001). However, even at the end of his course, Tajinder continued to use the full-shells explanatory principle, if not as frequently as when he began his A level course. Indeed, when he was reinterviewed some years later, his thinking demonstrated a reversion, so that explanations in terms of the needs of atoms to fill their shells once again dominated his answers (Taber 2003a).

In effect, Tajinder had entered the course with a commitment to a key idea he had acquired during school study; during the course, he had shifted away from this idea to some extent, towards the more physical explanations (i.e. explanations based upon physical principles such as the attraction between opposite charges) given in his course, but the original conception was tenacious and was the one he readily remembered some years after competing his course.

Although each student interviewed had somewhat idiosyncratic thinking, all drew to some extent, and usually as a major theme in their thinking, on a version of the full-shells explanatory principle. In general terms, progression in learning for these students was in large part about moving beyond this particular way of thinking, to adopt more scientifically acceptable ideas relating to electrical forces, energy minima and orbital interactions (Taber 1999b).

That is, *students entering the college chemistry course predominantly explained chemical bonding as being how atoms managed to fill their shells* (*or obtain octets of electrons or noble gas electronic configurations*). Although students might use different terminology, they would generally see the same species as stable: so generally (besides period 1, hydrogen and helium), references to full shells meant atoms with an octet of outer electrons, even in period 3 and beyond where technically such shells are far from 'full'. For the sake of a readable account, in this chapter I will ignore individual differences in how students described the desired electron

Covalent bonding	Ionic bonding
Forms between non-metallic elements	Forms between metallic and non-metallic elements
Due to sharing of electrons between atoms…	Due to transfer of electrons between atoms…
…so that atoms have full shells of electrons	…to give ions with full shells of electrons

Fig. 1 A bonding dichotomy: student conceptualisation of the nature and purposes of chemical bonding

configurations, as generally 'full shells' and 'octets' and 'noble gas structures' may be understood as synonymous in the context of learners' adoption of a 'full-shells explanatory principle' as the main driver for chemical processes.

So for these students, covalent bonds formed so that atoms could share electrons *to give them full shells*, and the ionic bond was the transfer of an electron from a metal atom to a non-metal atom, *to form ions with full outer shells*. Typical understanding may be summarised above (Fig. 1).

This outlines the typical understanding students brought from their school studies, and which formed the starting point for understanding presentations of chemistry at the submicroscopic level that they met in their advanced (post-school) studies.

Covalent Bonding as Electron Sharing

The notion that covalent bonding is the 'sharing' of electrons is not necessarily an alternative conception: chemists themselves often talk in this way. 'Sharing' is in effect a metaphor, but among chemists has become a 'dead' metaphor (Lakoff and Johnson 1999): one that through familiarity and convention has become adopted as an accepted label. For chemists, the notion of sharing *stands for* how an electron pair can bind two atomic cores through the electrical interactions between positive and negative electrical charges or implies that the shared electrons are understood to be placed in a bonding molecular orbital conceptualised as being formed by the overlap of atomic orbitals.

However, for students in the early stages of this study, sharing electrons formed a bond as it allowed the shared electrons to be counted in the valence shells of both of the sharing atoms and so allowed these atoms to be said to have full shells. That was considered both the reason for the bond forming and for why it acted as a bond. The students held an alternative conception that *the covalent bond formed and held atoms together in molecules because sharing of electrons allowed them to fill their shells*. Students commonly considered electron sharing as a sufficient explanation of bonding and so did not think in terms of electrical interactions.

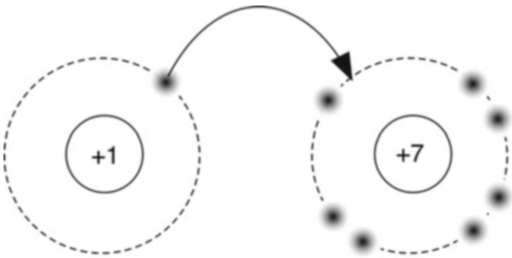


Fig. 2 Students commonly identify a chemically unlikely electron transfer between isolated atoms as being the ionic bond

Anthropomorphic Nature of Chemical Bonding

As students generally did not consider the physical forces acting when bonds formed nor conceptualise the bond in terms of an energy minimum – an equilibrium arrangement where attractive and repulsive forces balanced – their explanations of chemical bonding were anthropomorphic in nature (Taber 1998). They referred to atoms *wanting* or *needing* to fill their shells and forming bonds so that they could do so. In other words, in the absence of considering any physical mechanism (such as the force of attraction between a nucleus on one atom and an electron on a different atom), students talked as if atoms were sentient actors in the world. The way students described this was as if atoms *were aware* that they did not have full shells, *desired* full shells, and *actively* did something about it!

My interviewees were students in post-compulsory education and had achieved good grades in their school examinations, and I was rather surprised to find students apparently using anthropomorphic explanations of atomic behaviour without any apparent sense that this was only a metaphorical description. This was a feature I followed up in some interviews. I found some students seemed happy to talk extensively of the feelings and experiences of atoms without any sense of this being inappropriate or suboptimal as part of a scientific explanation. Other students seemed to acknowledge this *must be* a metaphoric form of description, but without this necessarily suggesting to them that it may be an inadequate one (Taber and Watts 1996/2005).

An Alternative Conceptual Framework for Ionic Bonding

When asked about ionic bonding, it was found that, for most students, the most salient idea was that of an electron transfer between atoms (Taber 1994, 1997, 1998). Indeed, for most students, this hypothetical electron transfer event was seen as the ionic bond (see Fig. 2).

This conceptualisation of the ionic bond tended to result in a way of thinking about ionic structures at odds with the models of science. This was described in

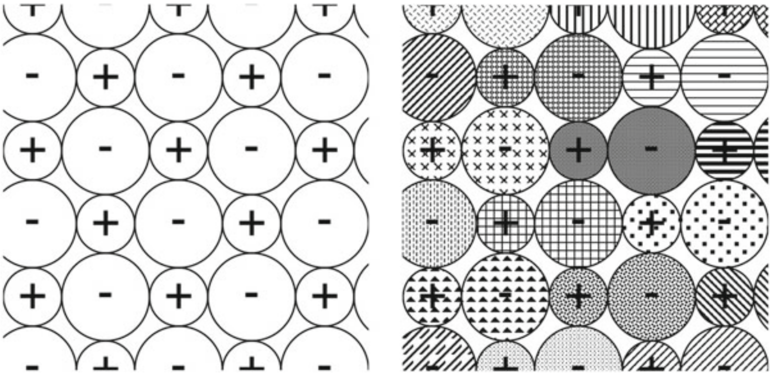


Fig. 3 When shown an image of an ionic lattice (*left-hand image*), some students will happily nominate pairs of ions as being bonded together but only attracted to other equally close counter-ions by weaker forces – conceptualising the structure as containing discrete molecule-like entities (*right-hand image*)

terms of an alternative 'molecular' framework for ionic bonding (Taber 1994), with four common features:

- The presence of molecules or molecule-like entities: that ion-pairs (or other units in more complex cases) formed by electron transfer exist as identifiable structural units in ionic lattices.
- The history conjecture: that an ionic bond only exists between ions that have experienced an electron transfer event together.
- The valency conjecture: that an atom can only form as many ionic bonds as the number of electrons it is able to donate or accept in forming an ion with a full outer shell.
- The 'just forces' conjecture: that there are two types of interaction in the ionic lattice, ionic bonds (where electron transfer has occurred) and just forces between adjacent ions that are not bonded through having experienced electron transfer.

These ideas form a coherent conceptual framework:

1. Defining the ionic bond as an electron transfer event leads to the history conjecture.
2. The history conjecture implies the valency conjecture.
3. This implies the presence of discrete molecular units such as ion-pairs within the lattice.
4. Which requires the 'just forces' conjecture to explain why the molecular units form a lattice.

When shown an image of a slice in an ionic lattice, showing a symmetrical arrangement of ions (similar to that shown in Fig. 3), some students were very happy to nominate which ions were bonded together through having been involved in electron transfer and so to assign ions to discrete units within the structure.

So, in effect, for many students, the ionic solid is conceptualised much like a molecular solid such as sulphur or dry ice, with strong bonds within the molecular units and weaker intermolecular forces holding these units together. Such a model of ionic solids is unhelpful, as it does not explain the strength of the lattice or the solubility of salts (as students tend to think that ion-pairs are the solvated species).

Student Thinking About Metallic Bonding

In the English interview study, it was found that students generally had strong commonalities in their thinking about both covalent and ionic bonds, tending to think of bonding primarily in terms of the bonding dichotomy presented above (Fig. 1). When students were asked about metallic bonding, they tended to demonstrate more variety in their thinking, with their ideas described as one of the following alternatives (Taber 2003b):

- There is no bonding in metals.
- There is some form of bonding in metals, but not proper bonding.
- Metals have covalent and/or ionic bonding.
- Metals have metallic bonding, which is a sea of electrons.

Some students were aware of the 'sea of electrons' model of metallic structure; yet, again, student thinking did not tend to be primarily in terms of electrical interactions, and the metaphoric nature of the 'sea' was not always appreciated. Some students drew metallic structures with vast excesses of electrons, reflecting the notion of metallic atomic cores as islands in the electron sea, but ignoring the need for electrical neutrality.

Some students who could not see how metal atoms could have full outer shells in a metal (their key criterion for a chemical bond) did not think metals had any kind of bonding, or at least not full chemical bonds. Others, however, considered the bonding to be ionic (with electrons donated to the lattice, allowing the metal cations stripped of valence electrons to have full shells) or in some way at least *like* ionic or covalent bonding. Some students were prepared to consider that the bond was a dynamic process, so that as the sea of electrons moved around, metal cores could be considered to have full shells at least part of the time. These various schemes allowed the students to make sense of why solid metals might have been formed by atoms that were trying to obtain full electron shells.

An Alternative Framework for Thinking About Chemical Stability, Change and Bonding

In the interview study, each student's ideas were explored in depth, and each demonstrated variations in the examples they used and how they explained different types of chemical structure. However, there was enough commonality to propose that there was a common conceptual framework of ideas that was widely adopted by students. The conceptual framework, the octet framework, is not then meant as a set pattern that students demonstrate in all its details, but a model of the common features of students' thinking, many of which were found across most of those interviewed (Gilbert and Watts 1983). This degree of commonality is perhaps not surprising given that there is a logical coherence to many of these ideas. That is, if one starts from the propositions that atoms (1) need to obtain full shells and (2) will act accordingly, then a particular way of making sense of the molecular world follows.

Extending Notions of Bonding

At the start of their course, the interviewees all knew about ionic and covalent bonding, and perhaps something about metallic bonding, but did not extend the concept of chemical bonding beyond that. During their college course, students learnt about bond polarity, dative bonding, hydrogen bonding, bonds in transition metal complexes, solvation/hydration, and induced-dipole–permanent dipole and induced-dipole–induced-dipole interactions. Much of this challenged their existing conceptions about the nature of chemical bonding and can be considered to be at least partially responsible for shifts in their thinking (Taber 2001).

Polar Bonding

In college level chemistry, students are taught that covalent and ionic bonds are in effect models of ideal cases, and that in most compounds, bonding is best understood as intermediate between covalent and ionic bonding. The metallic or non-metallic nature of elements is not taught as a dichotomy but in terms of the electronegativity scale, and it follows that ionic-covalent represents a continuum, with bonds found at different points along the dimension. However, for students who already understand bonding in terms of the ionic-covalent dichotomy, the conceptual change needed to see bonding instead in terms of a continuum proves to be a difficult shift – perhaps in part because it requires adopting a rather different *type* of ontology of bonding (Taber 2008b), when research suggests that adjusting aspects of personal ontologies may be something many students find problematic (Chi 1992).

In the interview study, it was found that students were open to accepting a category of polar bond but saw this as a distortion of and/or subtype of covalent bond (see Fig. 4). In part, the tendency to see polar bonds as distorted covalent bonds reflects the full-shells explanatory principle as the common starting point for thinking about bonding. When thinking in terms of an electrical model (as presented in the college curriculum), the bond can be considered as an electron pair

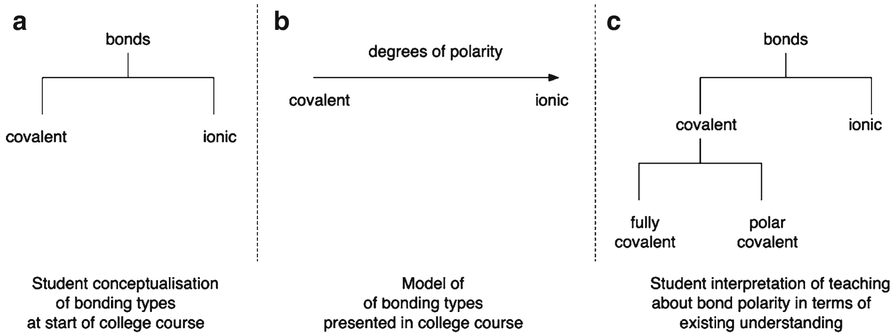


Fig. 4 Student conceptual change on learning about bond polarity

found between two atomic cores, and which may be completely at one side (ionic), evenly shared (covalent) or, more often, somewhere in between (polar). However, the notion of polar bonding does not readily follow from the full-shells explanatory principle, so – for students who consider an atom's needs to fill its shells as the driving force for chemical processes – teaching about bond polarity is *interpreted* as a secondary electrical perturbation, superimposed on the basic template of a covalent bond. This is not an explicit decision (Pozo and Gómez-Crespo 2005), but simply how teaching is interpreted in terms of the existing conceptual framework: given the starting point (i.e. Fig. 4a, understood as how atoms achieve full shells), learners interpret new teaching to form a hybrid mental model (Gilbert et al. 1982).

Intermolecular Bonding

Although the strongest bonds in chemistry tend to be those related to the ionic, covalent and metallic models, there are other interactions that are also very important. These include the interactions that allow solvation to occur, so that, for example, NaCl, with strong ionic bonds, is readily dissolved in the polar solvent water. Similarly, sulphur, wax and iodine are solids at temperatures where at least one substance with metallic bonding (mercury) is a fluid. The molecules in sulphur, wax and iodine are held together by van der Waals forces, that is, forces due to transient fluctuating dipoles in neutral molecules.

Students who have developed a way of thinking akin to the octet framework tend to think that chemical bonds are formed to allow atoms to achieve full shells, and so various types of dipole–dipole forces (whether due to permanent or transient dipoles) are therefore not considered to be types of chemical bonds. Whilst to some extent professional chemists also tend to distinguish strong chemical bonds from these weaker interactions, they recognise that (a) these different types of interactions can have overlapping ranges of 'strength', (b) intermolecular bonding can be highly significant, and (c) chemical phenomena are complex, and often several types of interactions can be considered to be operating simultaneously. In contrast, students tend to make a sharp distinction between (1) what they see as proper chemical bonds that can be explained in terms of the full-shells explanatory principle and (2) other effects which are 'just forces'.

Hydrogen Bonding

Hydrogen bonding is a particular case in point, as hydrogen bonding features as an important type of interaction in advanced chemistry courses – for example, explaining the high melting/boiling temperature of water (as well as several other important hydrides), and its low density as a solid, and having a significant role in the structure of proteins and nucleic acids. Indeed, students interviewed in the English study had often met hydrogen bonds in their biology lessons before they were taught about this type of bonding in chemistry classes.

Hydrogen bonds cannot be explained in terms of the full-shells explanatory principle, as the atoms involved are already formally bonded, and so from such a perspective, there is no reason why an oxygen atom, for example, which already has a full shell, would share a nonbonding electron pair with a hydrogen atom, which also already has a full shell of electrons. In the English study, it was found that when some students came across 'hydrogen bonds' in their biology lessons, they simply assumed this was a reference to covalent bond involving hydrogen and so misconstrued what the hydrogen bond was in the structures being discussed (Taber 1998). The label 'bond', and the significant role in holding structures together, was construed in terms of their existing notion of what counts as a bond.

Implications of the Ownership of Electrons

The anthropomorphic way of thinking and talking about atoms led some students to consider electrons to permanently belong to specific atoms (Taber 1998). This certainly played a part in thinking about ionic structures in molecular terms: two ions were considered bonded by their history, as the anion included an electron that actually belonged to the cation. Indeed, this was sometimes understood as a temporary arrangement, so it was suggested that in a double decomposition (precipitation) reaction, there would be a phase where a previous electron transfer was reversed, so that a new electron transfer could take place to form new ionic bonds (Taber 2002b).

Some students did not feel that the electrons in a covalent bond would be equally attracted to both nuclei, as (they argued) a nucleus would exert more force on *its own* electron. On bond fission, it was then expected that each electron would return to its own atom. The influence of this way of thinking appeared to even be retained on learning about orbital models of atoms and molecules, so that a student considered that the atoms retained their own hybridised atomic orbitals in the molecule despite knowing that those atomic orbitals are considered to have been recombined into molecular orbitals (Taber 2005).

Stability of Chemical Species

The full-shells explanatory principle is based around the stability of certain electronic configurations. This reflects the 'octet' rule, which is a useful heuristic for predicting stable molecules and ions. However, students commonly find the idea that full shells are stable to be especially attractive and so overgeneralise the rule. So students would commonly consider a neutral sodium atom to be less stable than a Na^+ cation because the latter has a full outer shell of electrons, an octet structure. Such a judgement is unhelpful in the absence of a chemical context. It was found that most students thought that once an electron was removed from a sodium atom, it would not be able to return, because the ion had a stable electronic configuration. Indeed, the students commonly thought that a sodium-seven-minus ion (Na^{7-}) with an electronic configuration of 2.8.8 would be more stable than a sodium atom (Taber 1998).

Perceptions of Chemical Reactions

A final area where 'octet thinking' seems significant is how students think about chemical reactions and *what changes in chemical change*. Not only do students commonly think that bonds form to allow atoms to obtain full shells, but many also suggest that this is the driving force for chemical reactions (Taber 1998). So for many students, chemical reactions occur to allow atoms to fill their shells. Of course, this means making *an assumption of initial atomicity* – such as in thinking about the formation of ionic compounds, where it is assumed the reactants are composed of isolated metal and non-metal atoms. The commitment to an assumption of initial atomicity can be sufficient to lead to students ignoring available information that should make it clear that, in most reactions, the reactants as well as the products comprise of species that already have stable electrical configurations.

Generalisability of the Octet Alternative Conceptual Framework

The octet framework (see Fig. 5) was initially developed as a model to describe common aspects of student thinking deriving from an interview-based study that probed into the understanding of chemical bonding and related topics, working with student volunteers studying chemistry in a single further education college in England (Taber 1998). These students showed common ways of thinking about

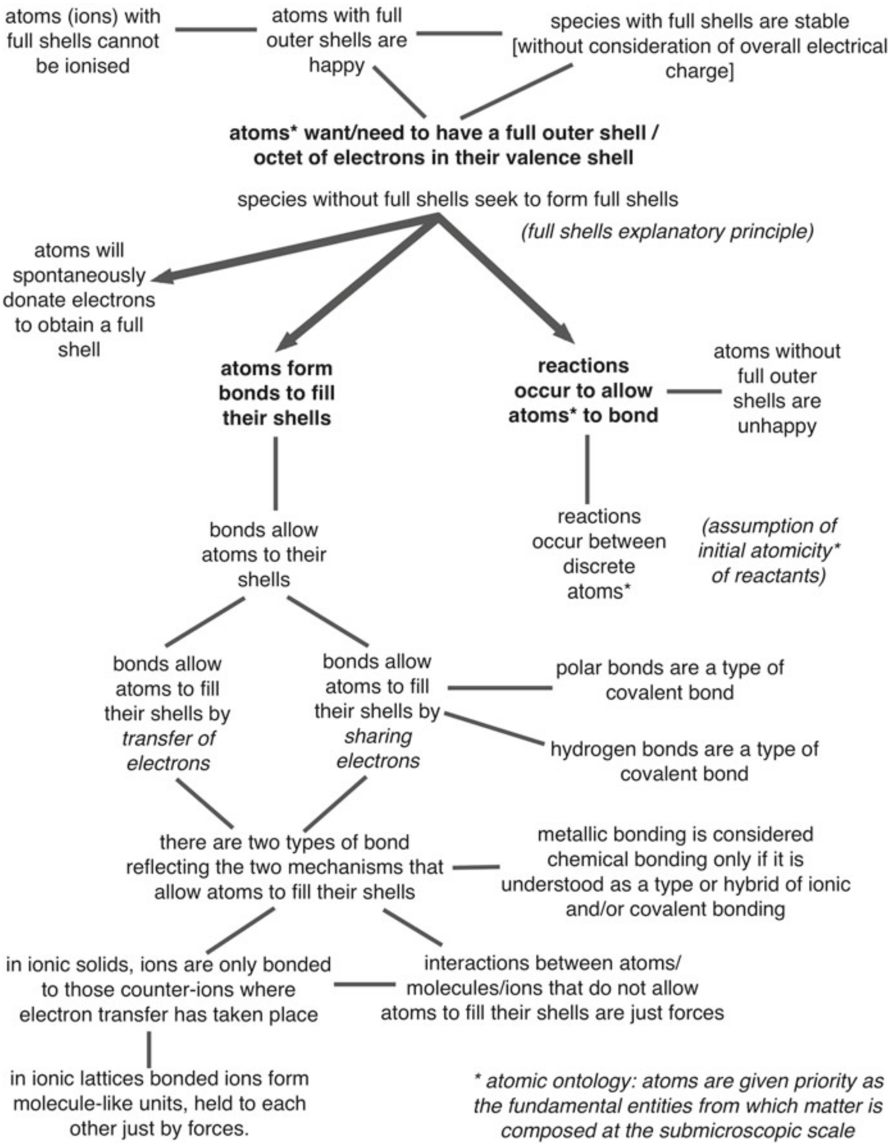


Fig. 5 The octet framework – an alternative conceptual framework comprising a network of ideas built around a core alternative conception

chemistry from early in their college course. As the college took students from a range of schools in the local area, and the interview sample had not been taught school chemistry by the same teachers, it seemed unlikely the common features of student thinking could be put down to an idiosyncratic teaching approach. Yet, it is clearly a major jump to assume that findings from students in one institution can be unproblematically generalised nationally or perhaps even globally.

However, there is strong evidence to suggest that at least some aspects of the octet framework are common features of student thinking in various institutional and national contexts. This evidence consists of:

(a) How aspects of the findings of the English interview study reflected findings reported by other researchers in other educational contexts.
(b) More recent studies in various national contexts have reported findings which seem to reflect aspects of the octet frameworks.
(c) Probes set up to test-out some specific aspects of the findings in the English study (Taber 2000a) have suggested that some aspects of thinking that are part of the octet framework are well represented among other student groups, both in the UK and beyond.

The latter strand of evidence was in particular supported by the Royal Society of Chemistry's 'Challenging Chemical Misconceptions' project (Taber 2002b) to provide classroom tools for teachers to diagnose student misconceptions (Taber 2002a). This provided the opportunity to enrol classroom teachers who would use diagnostic probes (some especially written for the RSC project) with their own classes. In this way, it was possible to test out the popularity of ideas elicited in the original interview study in a range of schools and colleges in different parts of the UK.

Some of these probes have since been used to survey groups of students studying chemistry in other countries, or in the case of one of the probes, as the starting point for developing a new instrument that was then applied in various national contexts. Space here does not allow an extensive review of all relevant studies but hopefully will allow the presentation of sufficient evidence to make the case that the octet framework seems to reflect aspects of student thinking about chemistry at the submicroscopic level across curriculum, national, and language contexts.

Anthropomorphism and Atoms

The octet framework is based around explaining chemical processes in terms of the needs (wants, desires) of atoms. Whilst chemists, and teachers, may use this kind of language, they are aware it 'stands for' underlying physical processes (e.g. electrical interactions). In the English study (Taber 1998), it was found that the 16–19-year-old students spoke as though the needs of atoms could be a sufficient basis for explaining chemical processes.

This reflects the earlier findings of Griffiths and Preston (1992) who had interviewed students of the same age in Canada and who reported that over half of their sample thought that atoms were 'alive'. In a study with US undergraduates studying chemistry, Nicoll (2001, p. 715) reported that 'it was noted throughout the course of the interviews and analysis that students ascribed sentience to atoms and molecules. Students continually referred to atoms "wanting" electrons; to "happy", stable molecules; and to atoms "seeking out" electrons'. She noted that 'it was difficult to determine whether students in this study actually did believe that the atoms and molecules were animate, or whether they were simply using the analogies that their teachers had given them' (p. 715). Nicoll offered the example of:

> Mellissa, a freshman in general chemistry for science and engineering majors, stated, for example, '… you have your noble gases that have that full octet: they're happy'. … she did not give any further explanation of all the orbitals being full, stability, or paired electrons. Rather, her complete explanation was that they were 'happy'. (p. 715)

In a more recent study undertaken with Turkish year 11 students, Ünal and colleagues (2010) reported students explaining chemical bonding in terms of the 'needs' of atoms to full their shells. Research undertaken with Swedish high school students has also found them using anthropomorphic accounts of atoms wanting or needing to obtain full electron shells (see the contribution by Taber and Adbo in chapter 'Developing Chemical Understanding in the Explanatory Vacuum: Swedish High School Students' Use of an Anthropomorphic Conceptual Framework to Make Sense of Chemical Phenomena', this volume).

Covalent Bonding as Electron Sharing

Chemists commonly use the metaphor of a covalent bond being a shared pair of electrons, but in the English interview study (Taber 1998), the 16–19-year-old students commonly thought that this was a sufficient definition of a covalent bond (as sharing electrons allowed atoms to obtain full shells). This was reflected in a case study of an Australian grade 11 student, where Harrison and Treagust (2000) report the student telling them that 'the atoms in a covalent bond share electrons so that each atom has a full outer shell' (p. 369).

Coll and Treagust (2001) report an interview study with Australian students at different levels and reported that 'learners view covalent bonding as the sharing of electrons, with the secondary school and undergraduate learners relating this specifically to the octet rule of full shell stability' (p. 369). The two postgraduate students interviewed in this study also referred to covalent bonding in terms of electron sharing, although this was one among several models used. In similar research carried out in Australasia (Aotearoa/New Zealand and Australia), Coll and Taylor (2001) interviewed students at three levels. They reported that the explanations of covalent bonding of secondary students were based on ideas of sharing electrons and the octet rule. Coll and Taylor also found that undergraduate and postgraduate students talked in terms of atoms sharing electrons. They reported an undergraduate chemistry student referring to how in an iodine molecule, the atoms would 'quite happily share with each other' (p. 180) and a postgraduate chemistry student talking of how a hydrogen atom ‘needs two’ electrons ‘to fill its valence shell’ where other atoms ‘need eight’ (p. 181) – although these students also had more scientific models available to think about the chemistry. In their Turkish study, Ünal and colleagues (2010) report year 11 students also talking of the sharing of electrons as a sufficient basis to explain the covalent bond.

Ionic Bonding as Electron Transfer

In the English interview study, it was found that students associated ionic bonding with electron transfer between atoms, leading to molecule-like entities (ion-pairs in the case of NaCl) within the lattice (Taber 1998). This reflected earlier research by Butts and Smith (1987) in Australia, who interviewed year 12 chemistry students and found 10 (out of 26 interviewees) referred to molecules of NaCl. These authors found few of their interviewees had a conventional understanding of the ionic bonding between ions in the lattice.

A diagnostic instrument, developed on the basis of student comments in the English interview study, was administered by class teachers to UK secondary school students (14–16-year-olds) and Advanced Level students (16–19-year-olds). It was found that students commonly agreed with statements based on the ‘molecular’ framework for thinking about ionic bonding, molecules being formed, and ions having ionic bonds only where electron transfer was considered to have occurred, and interacting with other neighbouring counterions just through forces (not chemical bonds). The overall results suggested that many students tended to hold a mixture of ‘molecular’ and target ideas, with some evidence of progression from school to college level study, especially among classes who had been taught the topic at Advanced Level. However, even among these students, some aspects of the alternative framework were popular (Taber 1997).

A version of the diagnostic instrument used in the UK study (Taber 2002a) was translated to produce Greek and Turkish versions. It was found that first-year university students in both these national contexts commonly judged true statements based on the alternative molecular framework for ionic bonding, although the patterns of response did vary between the three national contexts (Taber et al. 2012).

In their Australasian study, Coll and Taylor (2001) reported students appreciating the electrical nature of ionic bonding, although they also reported students associating ionic bonding with electron transfer. They reported one secondary student describing ionic bonding as ‘where they donate electrons and receive electrons’ (p. 179) and a reference to a sodium atom that ‘prefers’ to lose an electron (p. 180). In a study carried out in New Zealand, Coll and Treagust (2003) reported that among secondary level students they interviewed, the octet rule was seen as the sole driving force for the formation of ionic bonding, with electron transfer as its consequence. In a review of student answers on the Israeli matriculation examination taken by 17–18-year-olds, Levy Nahum and colleagues (Levy Nahum et al. 2004) found examples of references to sodium chloride consisting of two ions and comparisons of the strength of forces between molecules in sodium chloride and potassium iodide. In their study undertaken with Turkish year 11 students, Ünal and colleagues (2010) reported students talking about ionic bonds in terms of electron transfer, and one of the interviewees they quote explicitly referred to how this would form a molecule.

An Octet Criterion of Chemical Bonding: Metallic Bonding

In the UK interview study, the purpose of chemical bonding was seen by students as allowing atoms to have complete shells of electrons (Taber 1998), so students either did not consider metallic bonding as chemical bonding or tried to explain it in terms of covalent or ionic bonding types that made sense to them in terms of atoms achieving full shells (Taber 2003b).

Coll and Taylor (2001) reported that in their Australasian interview study, some of the secondary students tried to make sense of metallic bonding in terms of the octet rule and the formation of covalent bonds. One of the postgraduate chemistry students they interviewed admitted to not actually thinking of there being bonding in metals. Acar and Tarhan (2008) reported a study undertaken with 9th grade (15-year-old) students in Turkey where an intervention group learning about metallic bonding were found to demonstrate lower levels of common misconceptions after teaching than a control group. Among the control group, students were found to demonstrate high levels of misconceptions that

- The bonding in metals was ionic bonding, or the bonding in metals was like ionic bonding.
- The bonding in metals was covalent bonding.
- There were weak forces (rather than chemical bonding) holding a metal together.

These various alternative conceptions were found at levels in a range from about a quarter to over three-fifths of the control group (but at much lower levels in the intervention group).

An Octet Criterion of Chemical Bonding: Polar Bonding

In the English interview study, it was found that rather than seeing polar bonding as intermediate between the extreme case of the ionic and covalent models of bonding (a perspective taught in the college chemistry course and sensible when bonding is considered primarily as an electrical interaction), the English students tended to see bonding as in essence either ionic or covalent (understood in terms of the two distinct mechanisms for atoms completing shells), with polar bonding seen as a subcategory of the covalent case.

Prior to the English interview study, Peterson, Treagust and Garnett had reported a study with secondary students in South Australia where it was found that over a fifth of year 12 and a third of year 11 students ‘held misconceptions relating to bond polarity which indicated confusion regarding the unequal sharing and position of the electron pair in many covalent bonds…[and had not] not considered the influence of electronegativity and the resultant unequal sharing of the electron pair on bond polarity’ (Peterson et al. 1986, pp. 44–45). A more recent study using the same methodology among undergraduate students in Brunei found that about a third ‘had the misconception that equal sharing of electron pair occurs in all covalent [sic] bonds’ (Topper 1990, p. 41). In their study undertaken with Turkish year 11 students, Ünal and colleagues (2010) reported some of their interviewees discussing two types of covalent bond, with those formed between two atoms of the same type (i.e. same element) and polar bonds, which was simply the term used for covalent bonds formed between two different nonmetal atoms.

An Octet Criterion of Chemical Bonding: Hydrogen Bonding

Students in the UK interview study tended to limit their category of chemical bonding to those cases where bonding clearly enabled atoms to have full shells. Some students understood hydrogen bonding as a type of chemical bonding but only because they interpreted the hydrogen bond as simply a covalent bond involving hydrogen (Taber 1998). Similarly Henderleiter and colleagues (Henderleiter et al. 2001) reported from a study with US university students that during interviews, some undergraduates ‘confused hydrogen bonding with a covalent bond between hydrogen and some other atom’ (p. 1128).

Levy Nahum and colleagues (Levy Nahum et al. 2004) report an interview with a student who initially appeared to have a sound understanding of hydrogen bonding, but who on probing offered a confused account, and at one point indicated the O–H bond in a diagram of a water molecule as a hydrogen bond. One of the year 11 Turkish students quoted in Ünal and colleagues’ (2010) study explained that there was ‘no difference’ between a covalent and hydrogen bond, except in the latter case one of the atoms bonded was hydrogen, so that the hydrogen bond in HCl was a covalent bond (p. 19).

Inherent Stability of Species with Full Shells

A key aspect of student thinking in the UK interview study was that species with ‘full’ valence electron shells (usually actually octets of electrons) had an inherent stability (Taber 1998). This finding was followed up through the development of a set of diagnostic probes asking students to compare the stability of related species (Taber 2002a). When students from a range of institutions completed these probes, they commonly ascribed stability to chemically unlikely species, such as Na^{7-}, Be^{6-}, C^{4+}, C^{4-} and Cl^{11-}. Something like half of the students surveyed, thought that excited chlorine atoms with an outer-shell octet (i.e. configurations 1.8.8 or 2.7.8) would be more stable than the ground state (2.8.7) atom (Taber 2009a).

This notion that full shells or octets have some inherent stability influences the way students think about ionisation processes. Students demonstrate a number of common alternative conceptions about ionisation energy, suggesting they do not readily appreciate the basic electrical principles scientists use to think about atoms. In particular, some students suggest that ionisation will occur spontaneously to give a species with a full shell (Taber 2009a), and/or that once an ion with a full shell is produced, no further ionisation would be possible. In their Australasian study, Coll and Taylor (2001) reported one postgraduate chemistry student describing how a sodium atom ‘prefers’ to lose an electron (p. 180).

A diagnostic probe was prepared to explore student conceptions of this topic and completed by students in various institutions, demonstrating that alternative conceptions found in the UK interview study were common among students in other schools and colleges (Taber 1999c, 2002b, 2003c). Daniel Tan and colleagues based in Singapore took this instrument as the starting point for developing a two-tier multiple-choice instrument (Treagust 1988) to explore student understanding of the topic of ionisation energy (Tan et al. 2005), a process that involves cycles of interviewing students. It was found that the alternative conceptions identified among UK students were reflected in a large sample of Singapore students taking chemistry at the same (Advanced) Level (Taber and Tan 2007). The same instrument (translated as appropriate) was also used to collect data from students in several other national contexts (Spain, China, New Zealand and the USA), and again it was found that students in these contexts commonly demonstrated alternative conceptions based on the octet framework (Tan et al. 2008). It was also found that graduates preparing to be chemistry teachers in Singapore commonly demonstrated the same ideas (Tan and Taber 2009).

Driving Force for Chemical Reactions

In the original interview study, English students suggested that chemical reactions took place so that atoms could obtain full electron shells (Taber 1998). A classroom probe was prepared asking students why hydrogen reacted with fluorine (Taber 2002a). Despite the students being given a formulae equation for the reaction (i.e. showing that the reactants were H_2 and F_2), students commonly ‘explained’ the reaction in terms of the needs of the hydrogen and fluorine *atoms* to fill their shells (Taber 2002b) – even after being taught chemical ideas about why reactions occur (based on thermodynamics, bond enthalpies and the like). Interviews with Swedish high school students have also found students explaining that reactions occur because atoms look to complete their outer electron shells (see the contribution by Taber and Adbo in chapter 'Developing Chemical Understanding in the Explanatory Vacuum: Swedish High School Students' Use of an Anthropomorphic Conceptual Framework to Make Sense of Chemical Phenomena', this volume).

The Origin of the Alternative Conceptual Framework

The octet framework was developed as a model based on an interview study in one context, and it is important to acknowledge that although (as the previous section shows) elements of the framework appear to be demonstrated by students in various national contexts, there has not any research specifically been designed to replicate the findings of the English study as a whole. Despite this, there is a strong case for considering that ideas about atoms striving to fill their shells being the main driver for chemical processes seems to act as a common core to student thinking at upper secondary, college and even university level in a range of educational contexts.

It is possible to suggest several potential origins for the alternative conceptions that students develop (Andersson 1986; Claxton 1993; Gilbert et al. 1982; Hammer 1996; Smith et al. 1993; Solomon 1987; Talanquer 2006), although in reality these different factors are likely to interact (Taber 2009b). One source of such conceptions is the way people intuitively make sense of the physical world in which they live. So, for example, the common conception that a force is needed to maintain movement would seem to be an intuitive idea based on abstraction of experience of moving objects in the physical world (McCloskey 1983). According to diSessa (1993), a good many alternative conceptions that have been found in physics topics would seem to derive from the application of intuitive knowledge elements that seem to reflect the brain's natural tendency to abstract patterns from experience of the world.

Another source of alternative conceptions is the wealth of cultural ideas that are communicated informally through family, friends, media, etc. (Solomon 1987). The cultural origins of such ideas will be reflected in their incidence in different contexts (Brewer 2008). So notions that getting wet can lead to catching cold, and that sitting under a certain type of tree can lead to getting pregnant, tend to be common in different populations. Other ideas derive from the way individuals interpret linguistic cues or from their own analogical links between what they are told and already know. The expectation that neutralisation necessarily leads to a neutral product may be an example of how a common alternative conception can form in this way (Schmidt 1991). Annie, who interpreted the '+' and '−' symbols used to show ionic charge as indicating deviation from full shells (so that '+' means one electron *more than* a full shell), represents a more idiosyncratic example (Taber 1995).

The Role of Curriculum and Teaching in Encouraging the Octet Framework

The theoretical world of molecules, ions and electrons is not directly available to learners, so alternative conceptions are unlikely to be formed either by *direct* abstraction from experience or by acquiring folk knowledge (as talk about molecular structure and the like is seldom part of everyday lifeworld discourse). The example of Annie acquiring an *idiosyncratic* understanding of an aspect of chemists' representations of the molecular world should not surprise us: students learn about the unfamiliar by interpreting teaching through their existing repertoire of knowledge and ideas. Another student I worked with spoke of atoms with *electron shields*, having apparently misheard electron shells as an alternative term that made sense to him.

However, the existence of a very common alternative conceptual framework based on the needs and behaviours of atoms does present a problem. At present, there is limited definitive research to explain the origins of the octet framework as a common core to student thinking about chemistry at the submicroscopic level. After having worked on this issue for some years, my hypothesis about this is twofold.

In part, I consider teaching models and approaches partially to blame. Whilst the full-shells explanatory principle is not a valid one, many introductory school chemistry textbooks can be quite easily read as implying that bonds form so that atoms can fill their shells. Unfortunately, school chemistry seldom offers a viable explanation for why chemical reactions occur, so the octet rule seems to be adopted as an explanatory principle to fill the 'explanatory vacuum' (see also my work with Karina Adbo reported in this volume). Schematics representing bond formation often seem to imply that compounds are formed by the reaction of atomised elements (an isolated carbon atom reacts with four nascent hydrogen atoms, not two hydrogen molecules). Figures showing electron transfer (cf. Fig. 2) are presented when discussing the ionic bond, despite such figures having little relevance to the formation of ionic compounds. Teachers may use anthropomorphic language when discussing chemical processes, something research suggests makes many students more receptive to abstract topics (Day et al. 2008). The work of Daniel Tan with his graduate trainee chemistry teachers even suggests that in some cases, teachers themselves hold the alternative conceptions, so are presumably teaching flawed ideas to their classes in good faith (Taber and Tan 2011).

Chemical P-Prims?: The Role of Implicit Knowledge Elements in Developing the Full-Shells Explanatory Principle

However – even if it transpires that chemistry teachers worldwide are commonly teaching generations of students according to the octet alternative conceptual framework – that cannot be the whole story. Given that the curriculum generally offers more scientifically accurate models as target knowledge, there must be some reason why qualified chemistry teachers continue to teach in ways that lead to many of their students acquiring alternative conceptions about such core chemical concepts as bonding, stability and chemical change.

This would seem to be that some of these alternative ideas must be intuitively appealing. Although we would not expect students to directly develop intuitions about the world at the scale of molecules and ions (indeed, we know such ideas are counterintuitive for many learners), when students do meet atoms, molecules and the like in school science, their existing implicit knowledge of the world acts as the cognitive resource for making sense of the unfamiliar molecular realm. That is, students already have implicit knowledge elements that although not ‘about’ atoms and molecules, are cued in the context of being taught about the existence of these submicroscopic entities (Brown and Hammer 2008).

This is conjecture, but not pure speculation. Two of the common alternative conceptions about ionisation that seem to have appeal across national contexts would seem to be good candidates here. The notion that ‘full’ shells, with their symmetry, might be especially stable, and the way students understand nuclear force to be shared among valence electrons, seem to both reflect common patterns that can be abstracted from wide experience in the world (Taber and Tan 2007).

The work of diSessa and colleagues has uncovered many potential candidates for such intuitive knowledge elements, labelled as phenomenological primitives or p-prims, that are likely abstracted from common experience of the world and come to be applied to understand (or misunderstand) physical principles (diSessa 1983, 1993; Smith et al. 1993). These p-prims are considered to be domain independent and so should provide conceptual resources for making sense of all topics regardless of disciplinary boundaries. Certainly Andersson (1986) has proposed that a common intuitive knowledge element about the way agents bring about actions when changes occur in the world could act as a common core to learners’ conceptions across science.

To date, there has been limited research to develop this perspective in chemistry education. However, analysis of interviews into students’ explanations of basic physical and chemical changes carried out by Alejandra García Franco has suggested a number of possible candidates for implicit knowledge elements acting in chemistry, some of which may well turn out to link closely with diSessa’s p-prims (Taber and García Franco 2010).

Teaching and learning are complex processes, but Fig. 6 presents a schematic of how scientific ideas become simplified, interpreted and moderated as they are represented in classroom teaching and inform student learning.

Implications for Pedagogy and Directions for Research

There is scope for a lot more research into this topic. It is clear that students commonly develop alternative ideas about the submicroscopic models so central to chemistry, and that there are some strong commonalities in the alternative

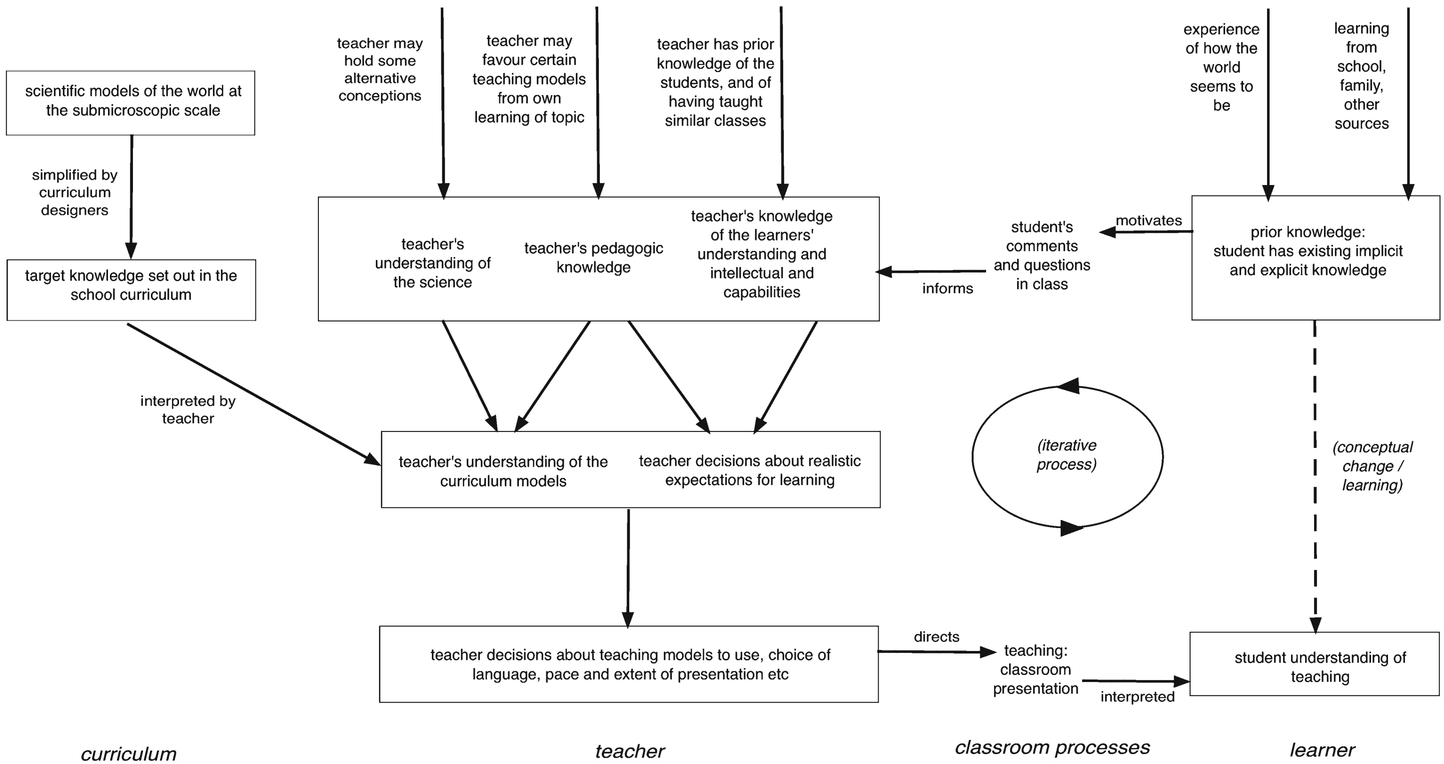


Fig. 6 Scientific ideas are modified both deliberately and inadvertently in classroom teaching

conceptions developed by many learners. It also seems clear that once students acquire something like the full-shells explanatory principle, it readily stands in place of more scientific understanding and impedes progression in learning. There is also a good case that the factors leading to students developing 'octet framework thinking' are not limited to a particular curriculum, language or teaching style.

The available evidence should certainly lead to teachers questioning certain common teaching practices: introducing bonding as a dichotomy of two main types, drawing imaginary electron transfer events when teaching ionic bonding, relying on anthropomorphic language to describe bonding and other processes, and overemphasising the octet rule would all seem to readily mislead students. Teaching bonding as primarily a matter of forces, emphasising how reactants (as well as products) tend to obey the octet rule, and stressing that stability is always a relative judgement (e.g. that overall charge is a factor as well as electronic configuration) would seem to be worth stressing more.

It seems that the teaching of chemical bonding is a topic that could be fruitful for researchers interested in teaching and teacher thinking, and – in particular – how knowledge is represented in curriculum and the classroom. Scientific knowledge is represented (i.e. necessarily as something rather different) in the formation of 'target knowledge' in the curriculum; and during the processes of classroom teaching, teachers then represent their own interpretations of that target knowledge in the decisions they make about level of treatment, concept sequencing and selection of teaching models (including choices of teaching analogies). Perhaps 'distortion' is inevitable in these processes of simplification and re-representation because of concerns about what students are ready to deal with or limitations in teachers' own subject knowledge or pedagogical content knowledge, for example (see Fig. 6). From the perspective of didactic transposition (Chevallard 2007), it would be expected that 'knowledge' would itself change its form in different institutional settings: chemical knowledge in the school science classroom adopts a different niche to chemical knowledge in the research laboratory or the discourse of the professional community. So, for example, anthropomorphic and teleological forms of explanation that may be criticised in the context of the work of the research scientist expected to offer mechanistic explanations may take on a different status among teachers more concerned with supporting student's attempts at meaning-making. This is perhaps an under-researched theme in science education, and the present topic area might offer a fertile context for enquiries.

There is certainly scope for research to develop our understanding of student thinking:

- To what extent is the octet framework common across different educational contexts?
- Are there variations in the incidence of students developing specific aspects of the framework across contexts that might give clues to how these ideas are acquired and reinforced?
- Can studies of the teaching of these topics in different classrooms relate students' developing thinking to the teacher's employment of different models, sequencing, language or emphasis?

The exploration of the importance of implicit knowledge elements has had much less attention in chemistry than in physics, and there is much scope for characterising the particular intuitive knowledge elements that students seem to be using to interpret teaching, with potential perhaps to develop a much more fine-grained constructivist approach to teaching (Taber 2008a): that is, knowledge of the available repertoire of primitive knowledge elements could inform the planning of instruction to take advantage of the way learners tend to implicitly understand the world.

The original interview study that was the first stage of the programme of research discussed here was undertaken with a necessarily modest number of informants questioned in some detail over a period of time, but the generality of some of the findings from that study have been tested out through survey-based techniques, showing how these different approaches are complementary in science education. The use of case studies provided some insight into the course of conceptual change in some individual learners. In particular, whilst the notion of learners having conceptual frameworks in science has been criticised in some quarters (Claxton 1993; Kuiper 1994), this certainly seemed an appropriate characterisation of the organisation of student knowledge in this topic (chemical bonding) in the 16–19-year-old learners investigated (Taber 1998). The nature and mechanisms of conceptual change have continued to be the subject of considerable scholarship and diversity of view (Vosniadou 2008), and it seems very likely that a full account of conceptual change in science learning will be nuanced and somewhat complex. For example, the research reported here found examples both of students adopting hybrid models (Justi and Gilbert 2000) when modifying existing understanding to accommodate somewhat disparate ideas and major (somewhat ‘revolutionary’) shifts (Thagard 1992) in the frameworks adopted in response to the slowly evolving ‘conceptual ecology’ (diSessa 2002) in which the chemical concepts were embedded. However, this work began with students entering college, and there would be much value in beginning a longitudinal study earlier during secondary education and possibly including microgenetic approaches (Opfer and Siegler 2004) to exploring students’ thinking during periods when the topic is being studied in class.

So there is much more work to be done. However, what seems very clear is that the outcome of current chemistry teaching for many students throughout the world seems to be the adoption of the core idea that the main driver for chemical processes is atoms ‘trying’ to fill their shells. That is scientifically dubious and impedes progression in learning the subject and so presents a serious challenge to chemistry educators.

References

Acar, B., & Tarhan, L. (2008). Effects of cooperative learning on students’ understanding of metallic bonding. *Research in Science Education, 38*(4), 401–420. doi:10.1007/s11165-007-9054-9.

Andersson, B. (1986). The experiential gestalt of causation: A common core to pupils’ preconceptions in science. *European Journal of Science Education, 8*(2), 155–171.

Brewer, W. F. (2008). Naïve theories of observational astronomy: Review, analysis, and theoretical implications. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 155–204). New York: Routledge.
Brown, D. E., & Hammer, D. (2008). Conceptual change in physics. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 127–154). New York: Routledge.
Butts, B., & Smith, R. (1987). HSC chemistry students' understanding of the structure and properties of molecular and ionic compounds. *Research in Science Education, 17*, 192–201.
Chevallard, Y. (2007). Readjusting didactics to a changing epistemology. *European Educational Research Journal, 6*(2), 131–134.
Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. N. Giere (Ed.), *Cognitive models in science* (Vol. XV, pp. 129–186). Minneapolis: University of Minnesota Press.
Claxton, G. (1993). Minitheories: A preliminary model for learning science. In P. J. Black & A. M. Lucas (Eds.), *Children's informal ideas in science* (pp. 45–61). London: Routledge.
Coll, R. K., & Taylor, N. (2001). Alternative conceptions of chemical bonding held by upper secondary and tertiary students. *Research in Science & Technological Education, 19*(2), 171–191.
Coll, R. K., & Treagust, D. F. (2001). Learners' mental models of chemical bonding. *Research in Science Education, 31*(3), 357–382.
Coll, R. K., & Treagust, D. F. (2003). Investigation of secondary school, undergraduate, and graduate learners' mental models of ionic bonding. *Journal of Research in Science Teaching, 40*(5), 464–486.
Day, C., Sammons, P., & Gu, Q. (2008). Combining qualitative and quantitative methodologies in research on teachers' lives, work, and effectiveness: From integration to synergy. *Educational Researcher, 37*(6), 330–342. doi:10.3102/0013189X08324091.
diSessa, A. A. (1983). Phenomenology and the evolution of intuition. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 15–33). Hillsdale: Lawrence Erlbaum Associates.
diSessa, A. A. (1993). Towards an epistemology of physics. *Cognition and Instruction, 10*(2&3), 105–225.
diSessa, A. A. (2002). Why "conceptual ecology" is a good idea. In M. Limón & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 29–60). Dordrecht: Kluwer.
Duit, R. (2009). *Bibliography – Students' and teachers' conceptions and science education*. Kiel: IPN – Leibniz Institute for Science Education. http://www.ipn.uni-kiel.de/aktuell/stcse/stcse.html.
Gilbert, J. K. (1995). Studies and fields: Directions of research in science education. *Studies in Science Education, 25*, 173–197. doi:10.1080/03057269508560053.
Gilbert, J. K., & Watts, D. M. (1983). Concepts, misconceptions and alternative conceptions: Changing perspectives in science education. *Studies in Science Education, 10*, 61–98.
Gilbert, J. K., Osborne, R. J., & Fensham, P. J. (1982). Children's science and its consequences for teaching. *Science Education, 66*(4), 623–633.
Glasersfeld, E. (1989). Cognition, construction of knowledge, and teaching. *Synthese, 80*(1), 121–140.
Griffiths, A. K., & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*(6), 611–628.
Hammer, D. (1996). Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions? *The Journal of the Learning Sciences, 5*(2), 97–127.
Harrison, A. G., & Treagust, D. F. (2000). Learning about atoms, molecules, and chemical bonds: A case study of multiple-model use in grade 11 chemistry. *Science Education, 84*, 352–381.
Henderleiter, J., Smart, R., Anderson, J., & Elian, O. (2001). How do organic chemistry students understand and apply hydrogen bonding? *Journal of Chemical Education, 78*(8), 1126–1130.
Justi, R., & Gilbert, J. K. (2000). History and philosophy of science through models: Some challenges in the case of 'the atom'. *International Journal of Science Education, 22*(9), 993–1009.
Kuiper, J. (1994). Student ideas of science concepts: Alternative frameworks? *International Journal of Science Education, 16*(3), 279–292.

Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh: The embodied mind and its challenge to western thought*. New York: Basic Books.
Levy Nahum, T., Hofstein, A., Mamlok-Naaman, R., & Bar-Dov, Z. (2004). Can final examinations amplify students' misconceptions in chemistry. *Chemistry Education Research and Practice, 5*(3), 301–325.
McCloskey, M. (1983). Intuitive physics. *Scientific American, 248*(4), 114–122.
Nicoll, G. (2001). A report of undergraduates' bonding misconceptions. *International Journal of Science Education, 23*(7), 707–730.
Opfer, J. E., & Siegler, R. S. (2004). Revisiting preschoolers' living things concept: A microgenetic analysis of conceptual change in basic biology. *Cognitive Psychology, 49*, 301–332.
Peterson, R., Treagust, D. F., & Garnett, P. (1986). Identification of secondary students' misconceptions of covalent bonding and structure concepts using a diagnostic instrument. *Research in Science Education, 16*, 40–48.
Pope, M. L., & Denicolo, P. (1986). Intuitive theories – A researcher's dilemma: Some practical methodological implications. *British Educational Research Journal, 12*(2), 153–166.
Pozo, J. I., & Gómez-Crespo, M. A. (2005). The embodied nature of implicit theories: The consistency of ideas about the nature of matter. *Cognition and Instruction, 23*, 351–387.
Schmidt, H.-J. (1991). A label as a hidden persuader: Chemists' neutralization concept. *International Journal of Science Education, 13*(4), 459–471.
Sjøberg, S. (2010). Constructivism and learning. In E. Baker, B. McGaw, & P. Peterson (Eds.), *International encyclopaedia of education* (3rd ed., pp. 485–490). Oxford: Elsevier.
Smith, J. P., diSessa, A. A., & Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *The Journal of the Learning Sciences, 3*(2), 115–163.
Solomon, J. (1987). Social influences on the construction of pupils' understanding of science. *Studies in Science Education, 14*(1), 63–82.
Taber, K. S. (1994). Misunderstanding the ionic bond. *Education in Chemistry, 31*(4), 100–103.
Taber, K. S. (1995). Development of student understanding: A case study of stability and lability in cognitive structure. *Research in Science & Technological Education, 13*(1), 87–97.
Taber, K. S. (1997). Student understanding of ionic bonding: Molecular versus electrostatic thinking? *School Science Review, 78*(285), 85–95.
Taber, K. S. (1998). An alternative conceptual framework from chemistry education. *International Journal of Science Education, 20*(5), 597–608.
Taber, K. S. (1999a). Alternative conceptual frameworks in chemistry. *Education in Chemistry, 36*(5), 135–137.
Taber, K. S. (1999b). *An explanatory model for conceptual development during A-level chemistry*. Paper presented at the British Educational Research Association annual conference, University of Sussex, Brighton. http://www.leeds.ac.uk/educol/documents/00001429.htm
Taber, K. S. (1999c). Ideas about ionisation energy: A diagnostic instrument. *School Science Review, 81*(295), 97–104.
Taber, K. S. (2000a). Case studies and generalisability – Grounded theory and research in science education. *International Journal of Science Education, 22*(5), 469–487.
Taber, K. S. (2000b). Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure. *International Journal of Science Education, 22*(4), 399–417.
Taber, K. S. (2001). Shifting sands: A case study of conceptual development as competition between alternative conceptions. *International Journal of Science Education, 23*(7), 731–753.
Taber, K. S. (2002a). *Chemical misconceptions – Prevention, diagnosis and cure: Classroom resources* (Vol. 2). London: Royal Society of Chemistry.
Taber, K. S. (2002b). *Chemical misconceptions – Prevention, diagnosis and cure: Theoretical background* (Vol. 1). London: Royal Society of Chemistry.
Taber, K. S. (2003a). Lost without trace or not brought to mind? – A case study of remembering and forgetting of college science. *Chemistry Education Research and Practice, 4*(3), 249–277.
Taber, K. S. (2003b). Mediating mental models of metals: Acknowledging the priority of the learner's prior learning. *Science Education, 87*, 732–758.
Taber, K. S. (2003c). Understanding ionisation energy: Physical, chemical and alternative conceptions. *Chemistry Education Research and Practice, 4*(2), 149–169.

Taber, K. S. (2005). Learning quanta: Barriers to stimulating transitions in student understanding of orbital ideas. *Science Education, 89*(1), 94–116.

Taber, K. S. (2008a). Conceptual resources for learning science: Issues of transience and grain-size in cognition and cognitive structure. *International Journal of Science Education, 30*(8), 1027–1053. doi:10.1080/09500690701485082.

Taber, K. S. (2008b). Of models, mermaids and methods: The role of analytical pluralism in understanding student learning in science. In I. V. Eriksson (Ed.), *Science education in the 21st century* (pp. 69–106). Hauppauge: Nova Science.

Taber, K. S. (2009a). College students' conceptions of chemical stability: The widespread adoption of a heuristic rule out of context and beyond its range of application. *International Journal of Science Education, 31*(10), 1333–1358.

Taber, K. S. (2009b). *Progressing science education: Constructing the scientific research programme into the contingent nature of learning science*. Dordrecht: Springer.

Taber, K. S., & García Franco, A. (2010). Learning processes in chemistry: Drawing upon cognitive resources to learn about the particulate structure of matter. *The Journal of the Learning Sciences, 19*(1), 99–142.

Taber, K. S., & Tan, K.-C. D. (2007). Exploring learners' conceptual resources: Singapore A level students' explanations in the topic of ionisation energy. *International Journal of Science and Mathematics Education, 5*, 375–392. doi:10.1007/s10763-006-9044-9.

Taber, K. S., & Tan, K. C. D. (2011). The insidious nature of 'hard core' alternative conceptions: Implications for the constructivist research programme of patterns in high school students' and pre-service teachers' thinking about ionisation energy. *International Journal of Science Education, 33*(2), 259–297. doi:10.1080/09500691003709880.

Taber, K. S., & Watts, M. (1996/2005). The secret life of the chemical bond: Students' anthropomorphic and animistic references to bonding. In J. K. Gilbert (Ed.), *Science education: Major themes in education* (Vol. 4, pp. 238–253). London/New York: Routledge.

Taber, K. S., & Watts, M. (1997). Constructivism and concept learning in chemistry – Perspectives from a case study. *Research in Education, 58*, 10–20.

Taber, K. S., Tsaparlis, G., & Nakiboğlu, C. (2012). Student conceptions of ionic bonding: Patterns of thinking across three European contexts. *International Journal of Science Education, 34*(18), 2843–2873.

Talanquer, V. (2006). Common sense chemistry: A model for understanding students' alternative conceptions. *Journal of Chemical Education, 85*(5), 811–816.

Tan, K.-C. D., & Taber, K. S. (2009). Ionization energy: Implications of pre-service teachers' conceptions. *Journal of Chemical Education, 86*(5), 623–629.

Tan, K.-C. D., Taber, K. S., Goh, N.-K., & Chia, L.-S. (2005). The ionisation energy diagnostic instrument: A two-tier multiple choice instrument to determine high school students' understanding of ionisation energy. *Chemistry Education Research & Practice, 6*(4), 180–197.

Tan, K.-C. D., Taber, K. S., Liu, X., Coll, R. K., Lorenzo, M., Li, J., & Chia, L. S. (2008). Students' conceptions of ionisation energy: A cross-cultural study. *International Journal of Science Education, 30*(2), 263–283. doi:10.1080/09500690701385258.

Thagard, P. (1992). *Conceptual revolutions*. Oxford: Princeton University Press.

Topper, D. (1990). Newton on the number of colours in the spectrum. *Studies in History and Philosophy of Science Part A, 21*(2), 269–279. doi:10.1016/0039-3681(90)90026-5.

Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education, 10*(2), 159–169. doi:10.1080/0950069880100204.

Ünal, S., Coştu, B., & Ayas, A. (2010). Secondary school students' misconceptions of covalent bonding. *Journal of Turkish Science Education, 7*(2), 3–29.

Vosniadou, S. (Ed.). (2008). *International handbook of research on conceptual change*. London: Routledge.

Macro–Micro Thinking with Structure–Property Relations: Integrating 'Meso-levels' in Secondary Education

Marijn R. Meijer, Astrid M.W. Bulte, and Albert Pilot

Introduction

It is not common to use structure–property relations for explaining a property of a substance or a material in secondary chemistry education. In the science education literature, macro–micro thinking is strongly connected to the particulate model and expressed in terms of a triplet relationship between macro-, (sub)micro- and symbolic levels (e.g. Gilbert and Treagust 2009). According to Talanquer (2009), the use of this triplet relationship has become almost paradigmatic in science education. Although in material and chemical engineering it is common to use structures at intermediate levels at the different scales between 10^{-1} and 10^{-7} m (Aguilera 2006; Gani 2004; Hill 2004), explicit description or use of macro–micro thinking with structure–property relations is hardly found in the educational literature (e.g. Meijer et al. 2009; Scheffel et al. 2009; Talanquer 2009).

In our work, we have described macro–micro thinking as a domain-specific case of systems thinking (Luisi 2002; Meijer 2011; Meijer et al. 2009). In line with the works of Millar (1990) and Besson and Viennot (2004), we have explored how to break up this 'huge' gap into smaller steps with intermediate 'meso-structures'. Materials are built up from smaller structural elements which themselves are built from lower-scale structural elements (Aguilera 2006). This system of subsystems becomes manifest when studying structures and properties of macroscopic objects and materials (cf. Aguilera 2006; Cussler and Moggridge 2001; Walstra 2003). An example is bread based on wheat. Bread can be defined as a final fixed form of dough. When scientists repeatedly 'zoom deeper' into dough, by using light or electron microscopes, they are able to distinguish certain structures, such as walls of gas holes, threads, granules imbedded in networks and entwined long molecules (Meijer 2011; Meijer et al. 2009).

M.R. Meijer • A.M.W. Bulte (✉) • A. Pilot
Freudenthal Institute for Science and Mathematics Education,
Utrecht University, Utrecht, The Netherlands
e-mail: a.m.w.bulte@uu.nl

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_20,

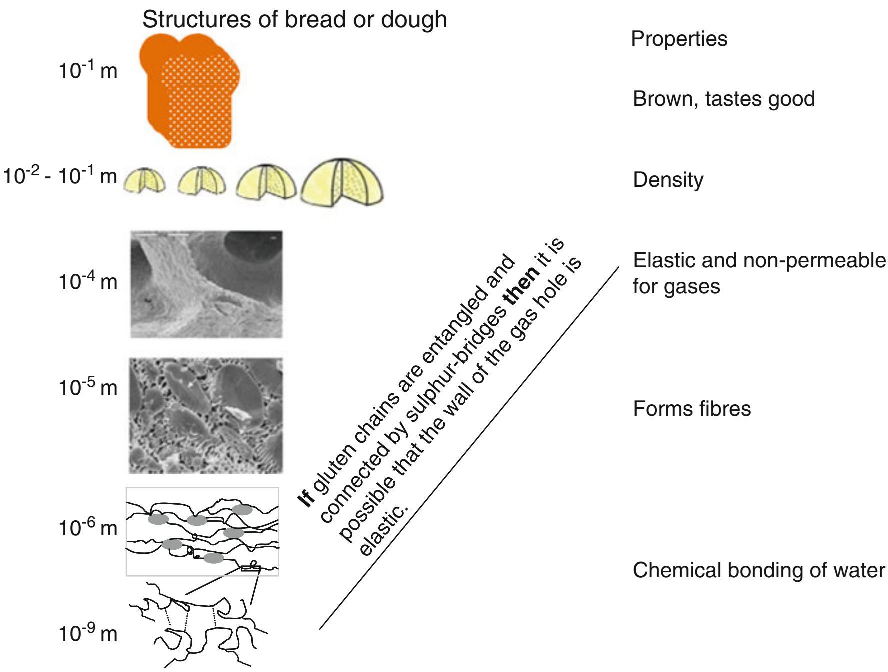


Fig. 1 A conceptual schema of structures in bread connected with a scale and properties (Meijer et al. 2009). This figure contains one example of a structure–property relation (SEM photos are reproduced with permission of Springer from Rojas et al. 2000)

These structures are examples of intermediate meso-structures at scales between 10^{-1} and 10^{-7} m, which are related to properties such as the elasticity of walls of gas holes, the strength of a thread, the flexibility of textile and the stiffness of cloths. Properties and structures can be attributed to the different scales within this system and represented in a conceptual schema (Fig. 1). Within such a conceptual schema, the meso-levels link macroscopic phenomena characterised by properties to submicroscopic models to facilitate a thinking process using the structure, the properties and their interrelations at the different levels.

'Structure' can be defined as the spatial distribution of the components in a system. Physical building blocks of such a system are regions which are bound by a closed surface (Walstra 2003). At least some of the properties within such regions differ from those in the rest of the system. 'Properties' can be defined as physical or chemical characteristics of a system (material): e.g. the elasticity of walls of gas holes or the capacity of gluten to absorb water.

A 'structure–property relation' is a causal relation between a structure at meso- or submicro-level and a property. Structure–property relations usually have a qualitative character (causal relations in words) and can be expressed as if-then clauses: '*if* this is an existing property, *then* it is explained by this type of structure' or '*if* this is the existing structure, *then* this property can be expected'. These relations are links between two different (meso-) levels and take a slanted diagonal direction (Meijer et al. 2009). See Fig. 1 for an example of this type of structure–property relation: if gluten chains are entwined and connected by sulphur bridges, then it can be expected that walls of gas holes are elastic.

The macro-level refers to the world in which visible, perceptible material and phenomena exist, e.g. gluten-free bread. The macro-level also refers to objects or materials which are closely connected to the human scale (0.1–1 m). The submicro-level is related to models of molecules and/or atoms and is connected to a scale between 10^{-10} and 10^{-9} m. All different meso-levels refer to structures with scales in between the macro- and submicro-level. We have chosen to use the term 'meso', although others terms are in use. The term 'microstructures' is used in material science, and the term 'nanostructure' is used in nanotechnology. Both terms may lead to confusion: 'microstructures' may be inadvertently confused with the submicro-level, whilst physicists also use the term 'nano' for the nanometre (10^{-9} m) level. Therefore, we follow the agreed terminology of macro and submicro (Gilbert and Treagust 2009) and use the term 'meso' for the levels in between. The number of meso-levels may differ from case to case, depending on the specific tasks and problems that are addressed with respect to macro–micro thinking (for a more extensive argument, see Meijer et al. (2009) and Meijer (2011)).

In this chapter, we explain how the use of the meso-levels is applicable for different examples. Subsequently, this chapter presents the strategies which were developed for the sake of learning macro–micro thinking, relying on the empirically established strategies for the case of developing gluten-free bread. This is followed by illustrating how these strategies can be integrated within two new curriculum units, which are a follow-up of our research study.

Macro–Micro Thinking Using Structure–Property Relations with 'Meso'-levels

The key idea developed in our work is macro–micro thinking with structure–property relations (Fig. 2; Craver 2001; Harré and Madden 1975; Meijer 2011; Meijer et al. 2009; Wilensky and Resnick 1999). The essence of macro–micro thinking is 'stepwise zooming in' through necessary meso-structures when explaining properties and 'stepwise zooming out' when predicting properties by means of systems thinking whilst using substructures of structures.

Substructures refer to subsystems connected by structure–property relations. The subsystems are defined by the structure–property relation because the interactions of these subsystems (structural elements) explain and/or predict an emergent property. For example, for explaining the brown colour of bread, a different set of meso-levels is necessary compared to the situation explaining the elongation of dough.

Explaining consists of the following: consider a structure which has a property. This structure is built up from substructures. The property of the structure could be explained by the interactions between the substructures (Rappoport and Ashkenazi

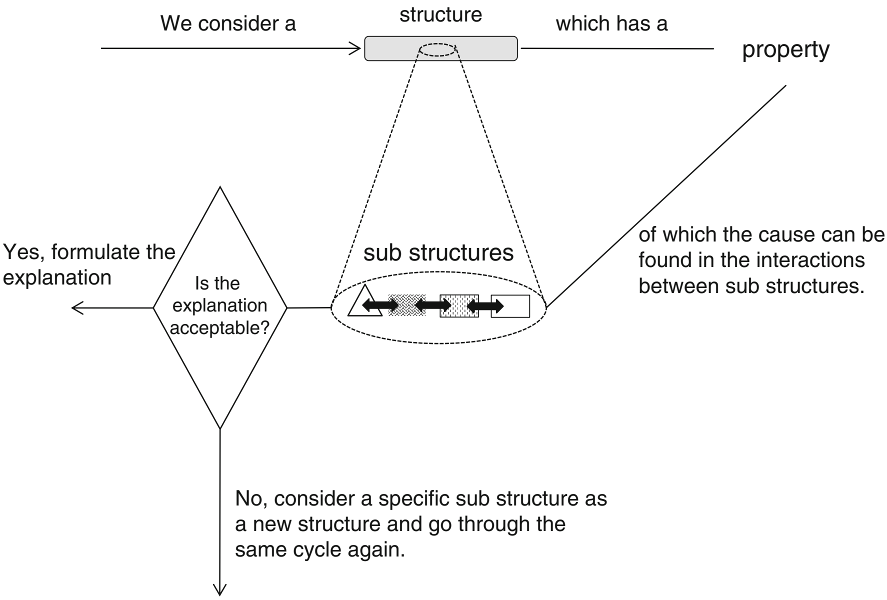


Fig. 2 Key idea of macro–micro thinking as 'stepwise zooming in' for explaining a property by using a substructure at a lower scale

2008). In this way, material structures can be interpreted as systems and subsystems with properties. Different subsystems can be distinguished from each other because they are separated because of differences in structures and properties. Structure–property relations are the specific relations between the substructures in the corresponding subsystem and the emergent property ('downward reasoning').

In the next description, macro–micro thinking linking structures to properties is illustrated with three examples, one from the domain of biochemistry, one from the domain of polymer chemistry and one from the domain of organic chemistry: (1) the elongation of wheat bread, (2) stiff and strong bike wheels made of Poly-p-phenylene benzobisoxazole (PBO) and (3) the stable character of benzene. The first two examples were chosen to illustrate the necessary use of meso-structures for relating structures to properties, whilst the third example shows a limiting case with properties at the macro-level directly related to structures at a molecular level. However, the key idea of macro–micro thinking as presented in the diagram of Fig. 2 applies for all three examples.

The first example is the elongation (property) of wheat dough (structure). Bread can be described with the following substructures: bread as a final form after the baking of dough, the walls of gas holes, the gluten network and the entwined gluten chains and the polypeptide chains with sulphur bonds (Fig. 3). Each of these structures has specific properties: these are, respectively, bite and resilience, elasticity of the wall, elasticity of the network and flexibility of the gluten chains.

In Fig. 3, macro–micro thinking is repeated four times before an acceptable explanation of the resilience of dough can be formulated. This explanation needs

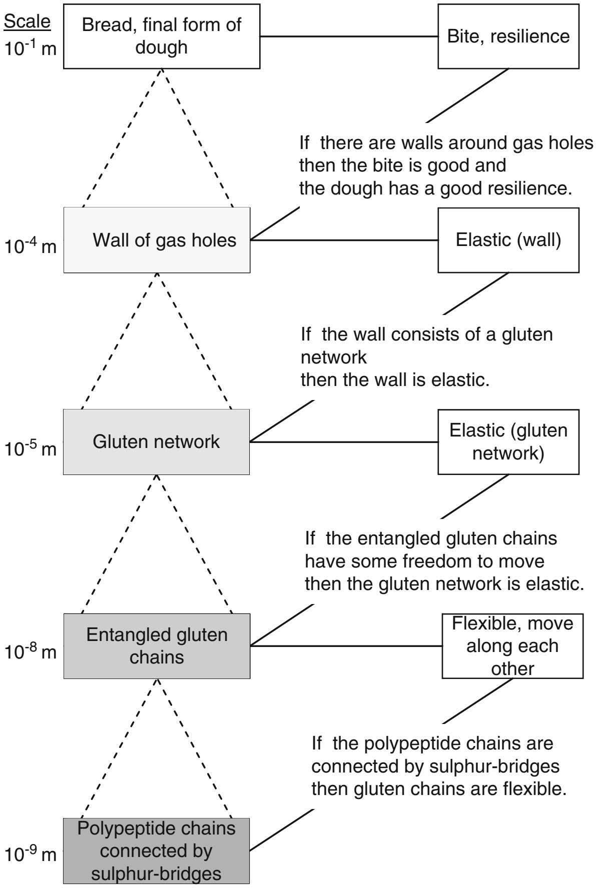


Fig. 3 The example of gluten-free bread. The property resilience is explained by a repetition of macro–micro thinking

four structure–property relations. In this case, it is not necessary to 'descend' to the level of the sequence of amino acids because the sequence of these amino acids does not provide new information which contributes to a deeper explanation of the resilience of dough (Meijer 2011).

In our empirical study, we have shown how pre-university students (age 17) were able to construct a conceptual scheme similar as is presented in Fig. 1, and related the specific task, to develop a gluten-free bread, to the necessity to have a dough which is flexible on the one hand but strong enough to capture CO_2 during fermentation. In fact, they were able to follow a thinking pattern as is presented in Fig. 3 to explain why dough prepared from wheat has the desired properties whilst corn dough without additives has an inferior quality.

The second example concerns the explanation of the high strength and stiffness of bike wheels (Fig. 4). The high strength of a bike wheel means that high stress is needed to deform the material. A high value for the stiffness refers to the elastic modulus (E) of a material; it describes the quotient between stress and strain when

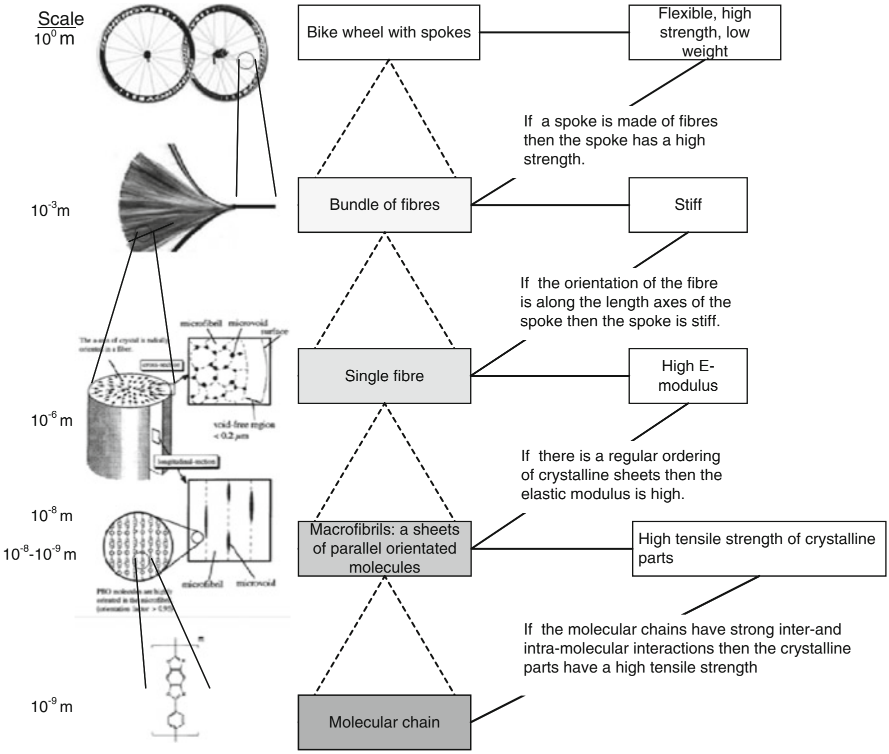


Fig. 4 The explanation of the flexibility and high strength of bike wheels made of PBO by using the key idea presented in Fig. 2 (Pictures adapted from http://www.spinergy.com & Kitagawa et al. 1998; the figures from this chapter are reproduced with permission of John Wiley & Sons, Inc)

this material undergoes elastic deformation. Poly-p-phenylene benzobisoxazole (PBO) has a very high E modulus (E_{PBO} is about 370 GPa), higher than the elastic modules of stainless steel (210 GPa) or polyethene (shopping bags, 0.7 GPa).

Figure 4 represents the meso-structures as subsystems within a bike wheel made of PBO: a spoke consisting of a bundle of fibres, a single fibre which is built up from regular microfibrils, ordered sheets of longitudinal directed molecular chains and molecular chains. Each of these subsystems, respectively, has the following properties: flexible and high strength, stiffness, high E modulus and a high tensile strength.

In this second example, downward macro–micro thinking takes place as follows. The high strength of a PBO spoke is explained by a bundle of fibres. However, the bundling is not the only explanation for the high strength; the bundle is stiff. The stiffness is explained by the same orientation of all fibre which has a high E modulus; under a high stress, the fibre shows a low deformation. The stiffness of a fibre is explained by a regular ordering of macrofibrils orientated along the length axes of the fibre. These macrofibrils are high crystalline parts with a high tensile strength. The crystalline parts consist of sheets of parallel oriented sheets of molecular chains.

The high tensile strength is caused by the high energy input necessary to break the covalent bonds and stability of the aromatic rings which are longitudinally orientated along the length axes of the macrofibril.

A third example is the rather low reactivity of benzene that emerges from the interaction between sp^2 orbitals of six carbon atoms (substructures). This inertness of benzene (property) is different compared to substances when the molecular structure of the molecule consists of five carbon atoms or when one carbon atom is replaced by nitrogen. Then the substance is much more reactive and less stable. In this third example, a property is explained by interactions between subsystems, the six delocalised electrons as a substructure. In this case, a property of a substance can directly be explained by structures at a submicro-level, as is frequently done in traditional chemistry education. Compared to the two other examples, these types of structure–property relations from the macro- directly to the submicro-level can be considered as a limiting case of more general macro–micro thinking as described in Fig. 2.

These examples show the potential to generalise macro–micro thinking in chemistry education. Explaining a property implies 'stepwise zooming in' until a property can be explained by interactions between subsystems or substructures. In most cases, macro–micro thinking implies several steps in repetition using several mesostructures or may relate properties and structure in a single step for explaining chemical properties of pure substances as a limiting case. These examples also imply that Johnstone's triangle (1991), with the paradigmatic use of a triplet relationship between macro, submicro and symbolic (Gilbert and Treagust 2009), may need revision. Addressing today's material and chemical engineering with its common use of structures at intermediate levels at scales in between 10^{-1} and 10^{-7} m (Aguilera 2006; Gani 2004; Hill 2004) requires that students do descend in more than one single step from macro- to submicro-level. When using the repetition of stepwise zooming in, the steps are mostly much smaller, with a discontinuity between each level of subsystems: there is not a gradual connection between the properties at the different levels. The proposed way of reasoning from macro- via meso- to submicro-level with structure–property relations seems continuous when considering sizes and scales; however, it is discontinuous in properties. The full implication of this, including the use of symbols and metaphors, is an issue for further research (Meijer 2011; Bulte and Van Mil 2011).

With respect to the *prediction* of properties, the 'upward reasoning', using structures and substructures, needs attention. Material engineers, nanoscientists and chemists design materials with specific properties. They can predict properties on the basis of expected interactions between substructures and then design such materials by manipulating substructures. This is 'upward reasoning' and is represented by the line upwards from substructures towards a property (Fig. 2). It is not evident how to evoke intuitive notions in students about emergence of properties or 'upward reasoning' (Chi 2005). Chi proposed two steps for 'upward reasoning' to avoid that students assign properties of a subsystem to the whole system. First, students should recognise and use the interactions between the subsystems. Second, students should become able to understand and describe what will happen with the whole system when asking themselves questions like 'what would happen if the interactions become weaker or stronger?' or 'what would happen if the molecules could not be brought into line with each other?' In this way, students are provided with an understanding of the underlying structure of emergent processes (Chi 2005) and emergence in chemistry (Luisi 2002).

Strategies for Learning Macro–Micro Thinking

1. Conceive a Material as System of Subsystems on Meso- and Micro-levels

The description of conceiving a material as a system of subsystems and so on forms the key idea of new teaching materials and curriculum units (Meijer 2011). It forms the first of seven design strategies listed below. The other design strategies (Table 1) are shortly described below including the underpinning with literature and evidence. The seven design strategies are subdivided into two clusters: systems thinking and transfer.

2. Use Intuitive Notions that a Property Can Be Explained/ Predicted by Structures Within the Material

This strategy implies the use of intuitive notion that a property of a material is explained by the nature of the material itself (Harré and Madden 1975; Meijer 2011; Pinker 2008; Talanquer 2009). The property of an object or a material can be understood by its nature under certain conditions. Objects and materials have certain properties even when those properties are not directly observable or measurable. Students have to identify the structure which explains this property. Structure–property relations connect a system (defined by a property) at macro-, meso- or submicro-levels with a subsystem at lower scales.

Table 1 Overview of design strategies for learning macro–micro thinking

Systems thinking	
1	Conceive a material as system of subsystems on meso- and submicro-levels
2	Use intuitive notions that a property can be explained/predicted by structures within the material
3	Use intuitive notions about 'structure' and 'property'
4	Use explicit scaling of structures
5	Use explicit terminology in modelling and use metaphors
Transfer	
6	Use subsequent analogous examples
7	Use interdisciplinary examples

3. Use Intuitive Notions About 'Structure' and 'Property'

Based on the empirical findings, we found that it is necessary to use intuitive notions of 'structure' and 'property' for an adequate concept development. We have to pay attention to the developments of both 'structure' and 'property', because both are key concepts in the presented way of macro–micro thinking. When triggering intuitive notions of students with respect to the concepts 'structure' and 'property', we found that students were able to formulate their own definition of these concepts. Intuitive notions of structure are 'an ordering, arrangement', 'how things are connected with each other' and 'how things are built'. For property, the intuitive notion can be 'what something can or does' and 'a function'. As a result of the students' own formulation of definition, their intuitive notions about 'structure' and 'property' can be used to categorise concrete structures and properties as a first step in concept development.

4. Use Explicit Scaling of Structures

Scaling requires special attention within the science curriculum (Jones and Taylor 2009; Tretter et al. 2006). Scaling is related to intuitive knowledge, which becomes difficult when references to human sizes are not available. Human beings have difficulty to use language effectively when the size of an object (e.g. at the level of the molecules or the universe) is far removed from their usual perspective, because spatial language is not only restricted to the size of objects but also to the way in which humans act (Pinker 2008). Explicitly pointing out the scale of a structure is necessary within macro–micro thinking using several meso-levels.

5. Use Explicit Terminology in Modelling and Use Metaphors

Language is an important medium for acquiring knowledge and for communication. It is essential that persons who communicate with each other use the same meaning regarding the object of their communication. A metaphor is a vehicle to give a concrete meaning to abstract entities and therefore is important in science and science education (Davidson 2001). Metaphors are always expressed in words connected to the macro-level. The use of metaphors therefore may hinder the intended conceptual development at meso- and submicro-level (Meijer 2011). Gentner and Wolff (2000) propose that metaphor comparison is an activity to connect metaphors with the concepts to be learned. Comparing and aligning requires an existing schema of concepts and representations. So, for acquisition of a new concept, it is presumed that a prior presence of the concept itself is needed (Arievitch and Haenen 2005; Ausubel 1968; Davidov 1990; Van Oers 1998).

6. Use Subsequent Analogous Examples

The issue of transfer implies the use of obtained knowledge in a different situation or task. Surely in the situation where one specific context is used, the transfer of concepts and thinking strategies may be more difficult when knowledge is strongly connected to a specific situation and strongly focused on one task (Gilbert 2006). The meaning of concepts is determined by the situation, that is, the context in which the task is relevant. For students, it is an effort to recognise deeper similarities and differences between situated tasks at a level of procedural steps and conceptual structures (Gentner and Wolff 2000; Gilbert et al. 2011). For facilitating transfer, a close alignment between the activities of different curriculum units addressing macro–micro thinking is necessary.

7. Use Interdisciplinary Examples

Systems thinking is an accepted way of thinking in biology education. Although biologists are interested in behaviour and function instead of properties, the presented way of thinking (Fig. 2) is applicable in systems thinking in biology (Verhoeff et al. 2008). Related to this, this chapter describes macro–micro thinking as a domain-specific case of systems thinking in chemistry. A possible next step is to study what is common and different between the ways of thinking in different disciplines. In this way, a more general approach to science education could be developed using more general 'Big Ideas' (Framework 2011), whilst taking the students' intuitive notions into account (Chi 2005).

Integrations of Strategies into Curriculum Units

Although the idea of macro–micro thinking using the meso-levels is rather new in chemistry education and was only recently investigated, we were able to introduce two new curriculum units in the new context-based upper secondary education of the Netherlands (Apotheker et al. 2010; Bulte et al. 2008a, b). Despite the difficulties when exploring this new type of education, we developed these two new units using the teachers' experiences in the years 2007–2010. We started in the autumn of 2007 till the spring 2011 and went through three cycles of design and improvements. The outcomes of our research project were used and further elaborated using the teachers' experiences. In the next, instances of the units are exemplified using the strategies for design as described above.

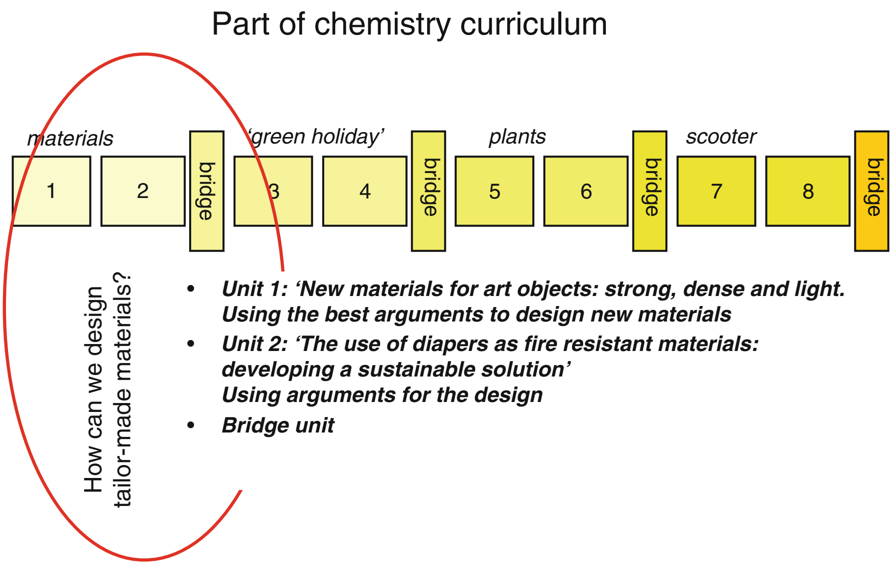


Fig. 5 Part of an experimental curriculum for students in the first year of upper secondary chemistry education (Apotheker et al. 2010)

Design Strategies 1 and 6: 'Conceive a Material as System of Subsystems on Meso- and Submicro-levels' and 'Use Subsequent Analogous Examples'; Two Successive Units – Composites and Superabsorbent Materials

The first unit is about composite materials in which students need to design a tailor-made material for art objects. The second unit is about the design of fire-resistant material as it can be based on the same superabsorbent polymer (SAP) material used in diapers. Used and wet diapers do not burn and can be used to protect a house from forest fires. However, the polyacrylic acid used in the diaper is not very environmentally friendly. Therefore students are asked to investigate alternatives, which are based on biodegradable materials. Both units lead students through the successive steps how to develop a tailor-made material. Both units deal with models that are helpful to explain and predict properties. Unit 1 uses only a few meso-levels; the models in this unit refer to structures at scales that are still imaginable with the human eye (10^{-4} m). Unit 2 deals with the effects of cross linking of polymers and different functional groups that may have an influence on the water uptake. The models used in the second set refer to structures that must be symbolic in their nature: to help students to cross this 'discontinuity' level. Figure 5 represents the curriculum outline of the successive unit outline of both units.

Table 2 Outline of successive student activities in unit 1 and unit 2

Student activity	Unit 1: materials for an art object	Unit 2: fire-resistant materials
1	Looking at objects from a perspective of the material scientist	A diaper filled with water is fire resistant: how?
2	Investigating the properties of different objects	What have learned about the diaper? What new knowledge is necessary?
3	Summarising properties of the materials	Studying different materials, water uptake and resistance to fire
4	Investigating materials with a microscope, relation to sizes and scale	What about the superabsorbent polymer (SAP) grains, wool and cotton? Experiments with water uptake
5	Summarising the properties in relation to structures	What about the SAP grains, wallpaper paste and alginate? Experiments with water uptake
6	Preparing materials from raw materials: clay, cement, gypsum and plaster cast. Measuring the mass/volume ratio (density)	Modelling the meso-structures of cotton (also sizes and scale), chains, beats and cross links; characteristic groups (size till 10^{-7} m)
7	Designing an art object	Summarising results: what material is suitable?
8	Investigating mechanical properties of the art object	Searching for new solutions; using sources from the literature: spheres of alginate and calcium chloride
9	Models of the structures (at 10^{-4} m) in relation to the properties (clay, gypsum, cement, plaster cast)	Testing the alginate spheres for fire resistance
10	Summarising the structure–property relations	Writing the report
11	Writing a plan/recommendation for the artist which materials to use	Writing a recommendation about the use of fire-resistant materials
12	Wrapping up new knowledge: summarising all structure–property relations	Wrapping up new knowledge: summarising all structure–property relations

Design Strategy 2: 'Use Intuitive Notions that a Property Can Be Explained/Predicted by Structures Within the Material' – Zooming in from the Problem, Raising Question, Do We Know Enough?

Both units have a similar structure. That is, students' activities start from a context with phenomena at a macroscopic level, and gradually, when necessary, the activities should raise questions about the 'deeper' internal structure of the material. Table 2 shows the successive student activities for both units.

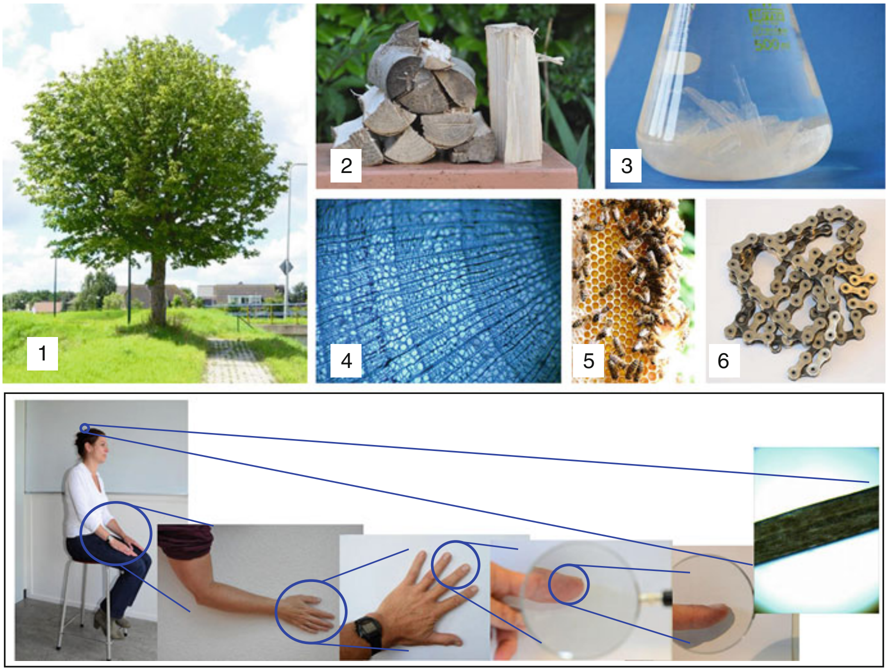


Fig. 6 Activity with photographs: defining structure in relation to size and scale

Design Strategy 3 & 4: Use Intuitive Notions about Structures & Use Explicit Scaling of Structures

These two strategies are combined within one activity in which students come to answer the questions A and B:

A. Structure and property as concepts, what do we mean by these words?
B. What are the sizes in relation to human body and to the metric system?

Unit 1 carefully introduces the use of the terms ‘structure’ and ‘property’. Activity 4 in unit 1 starts with pointing out different photographs and asking the students to sequence the pictures from big to small. Second, students need to relate each picture to a certain size: first in relation to sizes of the human body, a person, a hand, a finger, a nail and the thickness of a hair. Then these sizes are connected to sizes in the metric system: m, cm, mm and μm. This activity also asks students to formulate in their own wording what they think the term ‘structure’ means (Fig. 6). The result is discussed in the classroom (Meijer et al. 2009, pp. 208–209). Furthermore, unit 2 refers to these activities in unit 1 when models and sizes are related (e.g. in the activities 4 and 6; Table 2).

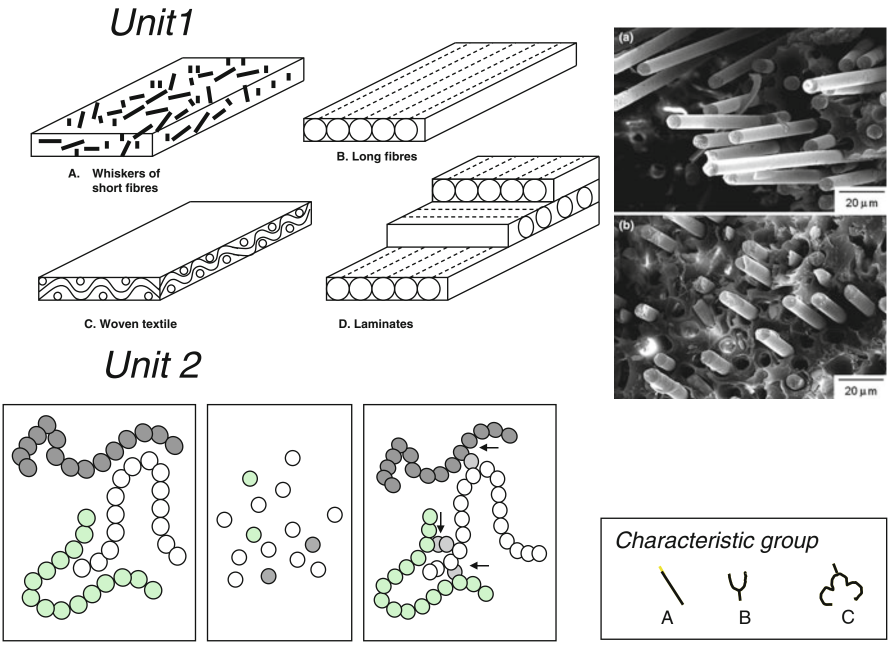


Fig. 7 The models used in unit 1 (*above*) and unit 2 (*below*), referring to metaphoric language (The SEM photos are reproduced with permission of Springer from Shen et al. 2009)

Design Strategy 5: Use Explicit Terminology in Modelling and Use Metaphors

The use of terminology that is metaphoric cannot easily be avoided. In the literature of materials science, many words are used: in relation to unit 1, for example, whiskers and fibres, and in unit 2, for example, beads, chains and characteristic groups. Figure 7 shows how symbolic models of materials are related to more iconic representations by using the SEM photograph. Activity 9 (unit 1, Table 2) relates the models to the materials the students have prepared: for example, plaster cast to model C in Fig. 7. In this way the rather metaphoric language and the models are related to the real object.

Similarities and differences become apparent. Unit 1 introduces the modelling activity, without 'passing' the usual discontinuity gap. Models are first used in relation to structures that can be visible for students. In this way, it may reduce the students' cognitive demand: first dealing with a modelling activity and relating to structures that are still visible, followed by a modelling activity using models that no longer can be 'seen' in unit 2. This step takes place when referring to cross links, polymer chains and characteristic groups in unit 2. This modelling activity is introduced after the students have investigated the water uptake of a SAP: more than 400 % of its own weight. This should raise the question: where does the water go? A SEM photograph of SAP does not give such an explanation.

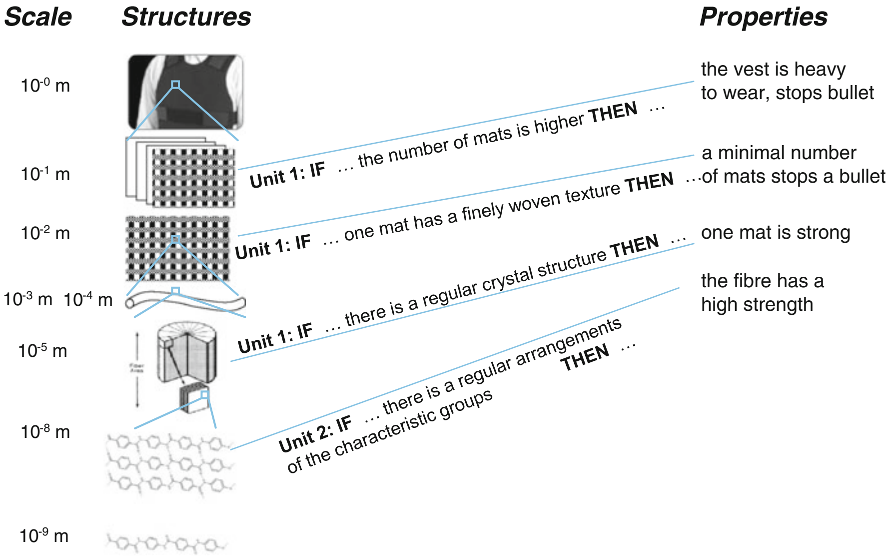


Fig. 8 Structure–property relations for the case of a bullet-free vest for used in unit 1 and extended in unit 2

Design Strategy 6: Use Subsequent Analogous Examples

This design strategy is used in several ways. The use of two subsequent units is explained above. Furthermore, in activity 12 (Table 2), both units use the same framework and the same example when students are asked to summarise their structure–property relations: bullet-free vest. However, in unit 1 the framework is only presented until the level of 1 mm, whilst in unit 2 the example as depicted in Fig. 8 is used. Furthermore, a subsequent (third) unit to bridge the two units (Fig. 5) consists of activities that summarise both units and help students to recognise the difference and similarities of the two subsequent units 1 and 2. This could be considered as a preparation for assessment.

Design Strategy 7: Use Interdisciplinary Examples – Relate to Biology

This way of macro–micro thinking is not unique to chemistry and material science. In biology and biochemistry, many issues deal with different levels of organisation and the relations between the levels: body, organs, tissues, cell, organelles and molecules. It is useful to help students recognise that macro–micro thinking can be applied in, for example, biology. A few student tasks in unit 1 relate to biological issues: for example, about the structure of bone related to osteoporosis, the structure of wood and bamboo and the structure of food. These examples provide students only with a minor connection, and at the moment of the design of both units, developing coherence between chemistry and biology was not the focus of attention. However, it is worthwhile to study how macro–micro thinking can be developed in coherence with biology education (Bulte and Van Mil 2011).

In Retrospect

The formulated design strategies used for the design of these new units were developed in an empirical study for one case, the case of developing gluten-free bread (Meijer 2011) with empirical evidence that the design strategies 1–4 led to the intended learning outcomes. As a result of the empirical study, the design strategies 5–7 were formulated as recommendations. In this chapter, we argue that the design strategies appeared to be useful for developing two new units. The specific details as described in this chapter lead to new case specific hypotheses, which are still subject of a new area of research in chemistry education.

Secondly, we also experienced that this way of macro–micro thinking is at present not part of the expertise of most teachers; the teachers need time to acquire new expertise. For this reason, we have been working with teachers to codevelop professional development programmes as a pathway for the development of the necessary teachers' expertise (Dolfing et al. 2012; Stolk et al. 2009a, b).

When the use of meso-levels in chemistry is a route to solve some of the motivational and cognitive problems students experience with the particulate nature of matter, this approach introduces new problems to the field. Challenging problems with complexity and organisational levels have become apparent in biology education and need to be addressed (Van Mil et al. 2013; Verhoeff et al. 2008). However, when biology and chemistry meet in new contemporary science issues, it is time to open up the traditional borders of the typical school science subjects in schools and in science education research. There are still many challenges ahead.

Acknowledgement The authors thank the reviewers of this chapter for their very valuable critiques and comments, which helped to improve the text. Mr. Fridolin van der Lecq is much acknowledged for providing the dedicated photographs of Fig. 6.

References

Aguilera, J. M. (2006). Food product engineering: Building the right structures. *Journal of the Science of Food and Agriculture, 86*, 1147–1155.

Apotheker, J., Bulte, A., De Kleijn, E., Van Koten, G., Meinema, H., & Seller, F. (2010). *Scheikunde in de dynamiek van de toekomst, over de ontwikkeling van scheikunde in de school van de 21ᵉ eeuw. Eindrapport van de Stuurgroep nieuwe Scheikunde 2004–2010* [Chemistry in a dynamic future, about the development of school chemistry in the 21st century. Final report New Chemistry 2004–2010]. Enschede: SLO.

Arievitch, I. M., & Haenen, J. J. (2005). Connecting socio cultural theory and educational practice: Galperin's approach. *Educational Psychologist, 40*(3), 155–165.

Ausubel, D. P. (1968). *Educational psychology: A cognitive view*. New York: Holt, Rinehart and Winston.

Besson, U., & Viennot, L. (2004). Using models at the mesoscopic scale in teaching physics: Two experimental interventions in solid friction and fluid statics. *International Journal of Science Education, 26*(9), 1083–1110.

Bulte, A. M. W., & Van Mil, M. H. W. (2011). *About parts and wholes in chemical and biological systems: reasoning, modeling and visualization strategies to connect macro and micro in chemistry and biology education.* In Symposium organised at the ESERA conference, Lyon.

Bulte, A. M. W., Houben, L., Meijer, M. R., & Pilot, A. (2008a). *Wat een kunst …, nieuwe materialen, sterk, dicht en licht, leerlingentekst* [What an art …, new materials, high strength, dense and light weighted; students' material]. Experimental module for curriculum development in the Netherlands. Retrieved July 2010, from www.examenexperiment.nl

Bulte, A. M. W., Meijer, M. R., & Pilot, A. (2008b). *Module 2: 'Reddende luiers bij brand, een toevallige uitvinding duurzaam maken' Versie 3.1. leerlingentekst, bronnenmateriaal en docentenhandleiding* [Diapers and fires, making an invention sustainable, students' materials and teachers' manual]. Utrecht: Freudenthal Institute for Science and Mathematics Education & SLO, Universiteit Utrecht.

Chi, M. T. H. (2005). Common sense conceptions of emergent processes: Why some misconceptions are robust. *The Journal of the Learning Sciences, 14*(2), 161–199.

Craver, C. F. (2001). Role functions, mechanisms and hierarchy. *Philosophy of Science, 68*(1), 53–74.

Cussler, E. L., & Moggridge, G. D. (2001). *Chemical product design*. Cambridge: Cambridge University Press.

Davidov, V. V. (1990). The concept of theoretical generalization and problems of educational psychology. *Studies in Soviet Thought, 36*, 169–202.

Davidson, D. (2001). *Inquiries into truth and interpretation*. Oxford: Clarendon.

Dolfing, R., Bulte, A. M. W., Pilot, A., & Vermunt, J. D. (2012). Domain-specific expertise of chemistry teachers on context-based education about macro-micro thinking in structure-property relations, accepted for publication. *Research in Science Education, 42*(3), 567–588. doi:10.1007/s11165-011-9211-z.

Framework. (2011). Committee on conceptual framework for the new K-12 science education standards, National Research Council. Retrieved at September 20, 2011, from http://www.nap.edu/catalog.php?record_id=13165

Gani, R. (2004). Chemical product design: Challenges and opportunities. *Computer and Chemical Engineering, 28*, 2441–2457.

Gentner, D., & Wolff, P. (2000). Metaphor and knowledge change. In E. Diettrich & A. Markamn (Eds.), *Cognitive dynamics: Conceptual change in human and machines* (pp. 295–342). Mahwah: Lawrence Erlbaum Associates.

Gilbert, J. K. (2006). On the nature of 'context' in chemical education. *International Journal of Science Education, 28*(9), 957–976.

Gilbert, J. K., & Treagust, D. F. (2009). Introduction: Macro, submicro and symbolic representations and the relationship between them: Key models in chemistry education. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education* (Model and modeling in chemical education, Vol. 4, pp. 1–8). Dordrecht: Springer.

Gilbert, J. K., Bulte, A. M. W., & Pilot, A. (2011). Concept development and transfer in context-based science education. *International Journal of Science Education, 33*(6), 817–837. doi:10.1080/09500693.2010.493185.

Harré, R., & Madden, E. H. (1975). *Causal powers, a theory of natural necessity*. Oxford: Basil Blackwell.

Hill, M. (2004). Product and process design for structured products. *AICHE Journal, 50*(8), 1656–1661.

Jones, M. G., & Taylor, A. R. (2009). Developing a sense of scale: Looking backward. *Journal of Research in Science Teaching, 46*(4), 460–475.

Kitagawa, T., Murase, H., & Yabuki, K. (1998). Morphological study on Poly-p-phenylene benzobisoxazole (PBO) fiber. *Journal of Polymer Science Part B: Polymer Physics, 36*, 39–48.

Luisi, P. L. (2002). Emergence in chemistry: Chemistry as the embodiment of emergence. *Foundations of Chemistry, 4*, 183–200.

Meijer, M. R. (2011). *Macro-meso-micro thinking with structure-property relations for chemistry education – An explorative design-based study.* Ph.D. thesis, Freudenthal Institute for Science and Mathematics Education, Faculty of Science, Utrecht University, FIsme Scientific Library (formerly published as CD-β Scientific Library), Utrecht, nr 65.

Meijer, M. R., Bulte, A. M. W., & Pilot, A. (2009). Structure-property relations between macro and micro representations: Relevant meso levels in authentic tasks. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education* (Model and modeling in chemical education, Vol. 4, pp. 195–213). Dordrecht: Springer.

Millar, R. (1990). Making sense: What use are particle ideas to children? In P. L. Lijnse, P. Licht, W. de Vos, & A. J. Waarlo (Eds.), *Relating macroscopic phenomena to microscopic particles* (pp. 283–293). Utrecht: CDβ Press.

Pinker, S. (2008). *The stuff of thought; language as a window into human nature*. London: Penguin.

Rappoport, L. T., & Ashkenazi, G. (2008). Connecting levels of representation: Emergent versus submergent perspective. *International Journal of Science Education, 30*(12), 1585–1603.

Rojas, J. A., Rosell, C. M. D., Barber, C. B., Perez-Munuera, I., & Lluch, M. A. (2000). The baking process of wheat rolls followed by cryo scanning electron microscopy. *European Food Research and Technology, 212*(1), 57–63. doi:10.1007/s002170000209.

Scheffel, L., Brockmeier, W., & Parchmann, I. (2009). Historical material in macro-micro thinking: Conceptual change in chemistry education and the history of chemistry. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education* (Model and modeling in chemical education, Vol. 4, pp. 215–250). Dordrecht: Springer.

Shen, L., Yang, H., Ying, J., Qiao, F., & Peng, M. (2009). Preparation and mechanical properties of carbon fiber reinforced hydroxyapatite/polylactide biocomposites. *Journal of Materials Science. Materials in Medicine, 20*(11), 2259–2265. doi:10.1007/s10856-009-3785-2.

Stolk, M. J., Bulte, A. M. W., De Jong, O., & Pilot, A. (2009a). Strategies for a professional development programme: Empowering teachers for context-based chemistry education. *Chemistry Education Research and Practice, 10*, 154–163.

Stolk, M. J., Bulte, A. M. W., De Jong, O., & Pilot, A. (2009b). Towards a framework for a professional development programme: Empowering teachers for context-based chemistry education. *Chemistry Education Research and Practice, 10*, 164–175.

Talanquer, V. (2009). On cognitive constraints and learning progressions: The case of "structure of matter". *International Journal of Science Education, 31*(15), 2123–2136.

Tretter, T. R., Jones, M. G., & Minogue, J. (2006). Accuracy of scale conceptions in science: Mental manoeuvrings across many orders of spatial magnitude. *Journal of Research in Science Teaching, 43*(10), 1061–1085.

Van Mil, M. H. W., Boerwinkel, D. J., & Waarlo, A. J. (2013). Modelling molecular mechanisms: A framework of scientific reasoning to construct molecular-level explanations for cellular behaviour. *Science Education, 22*, 93–118.

Van Oers, B. (1998). From context to contextualization. *Learning and Instruction, 8*, 473–488.

Verhoeff, R. P., Waarlo, A. J., & Boersma, K. T. (2008). Systems modelling and the development of coherent understanding of cell biology. *International Journal of Science Education, 30*(4), 543–568. doi:10.1080/09500690701237780.

Walstra, P. (2003). *Physical chemistry of food*. New York: Marcel Dekker.

Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems approach to making sense of the world. *Journal of Science Education and Technology, 8*(1), 3–19.

Learning and Teaching the Basic Quantum Chemical Concepts

Georgios Tsaparlis

Introduction

Quantum chemistry provides a unifying set of models or, equivalently, a theory for the interpretation of any chemical behavior. As a consequence, the undergraduate quantum chemistry course (usually as part of the physical chemistry course) is a strong constituent of the education and training of chemists. It is recognized, however, that this course poses considerable conceptual challenges to students. An ambitious Greek new graduate student, doing studies in theoretical chemistry, asked about the difficulty of the various parts of the undergraduate physical chemistry course commented: “More difficult is quantum chemistry because its concepts put you in a different logic: particles move differently than what we know in the world we live in, and this is something peculiar” (Tsaparlis, unpublished results).

Quantum chemistry is the application of the theory of quantum mechanics to chemistry. It describes matter (as a rule, approximately) by means of mathematical functions and expressions that derive from Schrödinger’s wave mechanics. As early as 1929, Paul Dirac felt able to state: “The general theory of quantum mechanics is now complete… The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known” (Dirac 1929, p. 714). Pauling and Wilson (1935) realized that “quantum mechanics is essentially mathematical in character, and an understanding of the subject without a thorough knowledge of the mathematical methods involved and the results of their application cannot be obtained” (p. iii). However, the mathematics of quantum mechanics is somehow different; it is *esoteric* to the subject. As Coulson put it, “mathematics is now so central, so much ‘inside’ that without it cannot hope to

G. Tsaparlis (✉)
Department of Chemistry, University of Ioannina, Ioannina, Greece
e-mail: gtseper@cc.uoi.gr

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_21,

understand our chemistry. … These [quantum-chemical] concepts have their origin in the bringing together of mathematics and chemistry" (Coulson 1974, p. 17).

Although one can derive the Schrödinger equation with entirely classical arguments (Fong 1962; see also Tsaparlis 2001) (with Planck's constant *h* serving as the bridge between classical and quantum mechanics), one has to admit that quantum mechanics has brought a new way of thinking about the physical world at the submicroscopic level. The physics of quantum chemistry is different from classical physics. According to Castro and Fernandez (1987), thinking abilities beyond Piagetian formal operations may be required for an adequate understanding of quantum mechanics (and relativistic) issues. These *postformal operations* include what Borkoff and von Newmann (1936) have described as *quantum logic*.

The basic quantum chemical models and concepts, such as atomic orbitals (AOs), molecular orbitals (MOs), and hybridization, are now part of the general chemistry and the introductory inorganic and organic chemistry courses. They are also standard components of most senior high school curricula at advanced or special levels or streams. In this chapter, after an overview of related educational literature, I review my research group's studies on misconceptions and learning difficulties occurring with students at the high school and at the university level. University chemistry students who had passed the quantum chemistry course (at the physical chemistry level) were the focus of the first study, which monitored their understanding of key quantum chemical concepts. At the high school level, we compared students' performance in questions that tested recall of knowledge or application of algorithmic procedures with that on questions that required conceptual understanding and/or critical thinking. Further, we examined beginning university students' levels of explanations, levels of models, and misconceptions. Turning to a teaching intervention, we tested for deep understanding and critical thinking about the basic quantum chemical concepts taught at twelfth grade with the aim to achieve conceptual change in students. The chapter is concluded with a general discussion, implications, and recommendations for learning and teaching.

Models of Quantum Chemistry and Students' Misconceptions

Halloun assumed that "a given scientific model is a representation of a particular pattern in the real world" (Halloun 2007, p. 665). With quantum chemistry as a research field in mind, Pople, in his 1998 Nobel lecture, defined a theoretical model for any complex process as an *approximate but well-defined* mathematical procedure of simulation (Pople 1999). Nersessian (1992) considered models as starting points for the development of theories. A set of models or families of models constitute a scientific theory (Halloun 2007). Kuhn (1970) considered models as constituent parts of theories; the other constituents of the theories are "symbolic generalizations" (which include laws and definitions), "values," and "exemplars."

Students' understandings at the submicroscopic level, and especially at the quantum chemistry level, may not always be scientifically correct and may lead to knowledge that is different from or inconsistent with the accepted scientific definition (Nicoll et al. 2001). In science education, such knowledge is described by the terms "*alternative conceptions*" or "*misconceptions*" (Driver 1983; Taber 2002a). Research has revealed a large number of student misconceptions about the basic quantum chemistry concepts at the high school or the pre-physical chemistry tertiary level. Below I review older and recent relevant studies (see also Tsaparlis 2008). The review is organized about some broad categories that better reflect the underlying student reasoning problems.

Classical Thinking and Generation of Hybrid Models

Quantum chemistry was preceded by old quantum "theories," such as the Rutherford, Bohr, and Sommerfeld atomic models. These models were *deterministic* in nature; for instance, according to the Bohr model, electrons in atoms move on fixed orbits, having fixed energies. It is very common for students to confuse between electron shells and electron clouds (Harrison and Treagust 2000). Taber (2002a, b) found that British advanced high school (A level) students had real difficulties with orbital ideas, treating the terms orbitals, shells, and orbits interchangeably. Research has shown that students at all levels are not comfortable with current models of the atom and the molecule. They prefer the simple abstract models: the Bohr model of the atom (Fishler and Lichtfeldt 1992; Nicoll 2001; Petri and Niedderer 1998), the octet rule (Coll and Taylor 2002), and simple models of chemical bonding (Coll and Treagust 2001, 2002). These preliminary models are very stable and resistant to change with the quantum mechanical models.

Behind many misconceptions is thinking in classical/deterministic terms: "electrons move around the nucleus in definite orbits"; "the electron is always a particle"; "electrons move along wavy orbits around the nucleus"; and "the overlapping/mix-up of the conceptual frameworks of classical and quantum physics" (Ireson 2001; Kalkanis et al. 2003; Olsen 2001). Such models operate at different levels of quantum theory (*hybrid models*), and this mix-up forms epistemological obstacles to the acquisition of the proper scientific knowledge (Sánchez Gómez and Martín 2003).

The Concept of Orbital

The orbital is the most fundamental concept of quantum chemistry. Students' first encounter with this concept is in their high school or the general and/or first university year inorganic chemistry courses, where the orbital is presented as a region in space inside which there exists a given probability for an electron to be encountered. Unfortunately, a definition of an AO as a one-electron, well-behaved function that can describe – more or less successfully – the behavior of an electron in an atom is lacking in these courses. This mathematical definition follows directly from the solutions of the Schrödinger equation of the hydrogen atom.

Nakiboğlu (2008) used a word association test to detect strongly and weakly related concepts within a conceptual organization. The high school students of the study did not know concepts such as quantum numbers and orbital types, but only the orbital concept appeared to be part of their knowledge and that at the weakest level. Park and Light (2009) worked with three particularly high-achieving students and considered the concepts of "probability" and "energy quantization." They suggested atomic structure as a possible "threshold concept" that provides valuable information for understanding students' learning difficulties and insight into how they may be addressed.

According to Zoller (1990), problems related to understanding the meaning of fundamental concepts, such as the concept of AO and the real meaning of the *s*, *p*, *d*, and *f* orbitals, are responsible for misconceptions and misunderstandings of the model of hybridization. Nakiboğlu (2003) also found in her students serious misconceptions about hybridization, arising from problems with prerequisite knowledge, especially with the concept of AO.

Models of Chemical Bonding

Coll and Treagust (2001, 2002) examined the advanced (upper secondary, undergraduate, and graduate) students' mental models of chemical bonding. All these learners preferred simple, realistic models and related to more abstract models only in the context of tests or examinations. Furthermore, the students struggled to use their mental models to explain the physical properties of covalently bonded substances.

Taber's British A-level students became confused between the mathematical modelling (the *Linear Combination of AOs*, LCAO) of MO formation and the orbitals themselves, referring to "linear orbitals" (Taber 2002a, b). As a consequence, the students did not readily develop the concepts of MOs: "as an appreciation of MOs is built upon an understanding of the simple atomic case, it is to be expected that attempting to teach the more complex examples whilst students have limited conceptualizations of the simpler case may only compound their difficulties" (Taber 2002b, p. 169). Taber (2005) drew a "typology of learning impediments," which can be used by the instructors for diagnosing the origins of students' difficulties in learning orbital ideas.

The models and concepts of the old quantum "theories," to which students have been exposed during high school, represent earlier models, which in many ways are still useful today even in actual scientific practice. In the strict sense, these models and concepts should not be considered as misconceptions. However, they form deep theoretical constructs that are difficult to change and can impede the interpretation of scientific information. They constitute what Vosniadou et al. (2001) have termed *entrenched presuppositions*. Old quantum theory is the prior knowledge that ideally should serve as a springboard for learning the current quantum models, but, for various factors, the new knowledge may be interpreted by the old approach or as a hybrid of both the new and old approaches. In this way, the old models very often constitute a learning impediment for the desired transition from deterministic to probabilistic models, and, as such, they are operationally equivalent to alternative conceptions.

It follows from the above that the elementary, imprecise, and mostly pictorial relevant previous instruction at high school and in the general chemistry course is responsible for the fact that students arrive at the quantum chemistry course carrying with them misconceptions and incomplete knowledge about the basic quantum chemical concepts.

Study I: Chemistry Graduates' Knowledge and Understanding of Quantum Chemistry Concepts

Models and theories deal essentially with conceptions and concepts. Conceptions are taken as "pieces of knowledge" (DiSessa 1988) that point to local representations of particular instances and constitute a static description of a system. On the other hand, mental models are global, involve interrelated elements, and refer to dynamical situations. According to Franco et al. (1999), conceptions express a domain-specific understanding of particular ideas and phenomena, and as such they are not generalizable into overall interpretative systems. Halloun (2007) places models between a scientific theory and its concepts, assuming that a scientific theory has a model-centered, "middle-out" structure.

A basic question about quantum chemistry concepts is whether chemistry graduates have a deep and precise understanding of modern concepts of AOs, MOs, and related concepts. In *Study I*, I carried out an analysis of examination data of Greek chemistry students who had passed the compulsory quantum chemistry course (Tsaparlis 1993, 1997). Note that all high school chemistry teachers in Greece must have an undergraduate degree in a science discipline (preferably in chemistry) so that the knowledge and understanding students gained in the particular course studied is representative of the knowledge that chemistry teachers in Greece would have.

End-of-semester, final examination data from the compulsory quantum chemistry course taught in a Greek university in the fourth semester of the 4-year (eight semester) chemistry degree program were used. The examination questions aimed at testing knowledge, understanding, and application, with some items such as problems or qualitative critical questions demanding analysis, synthesis, and evaluation. Six examination papers, covering a period of three consecutive years, were used. The cumulative data for the whole period involved 506 examinees ($M = 37.6$ %), but the study was restricted to the 212 successful students who passed the course in this period ($M = 59.1$ %).

Most students failed to provide the mathematical definition for an AO as "a one-electron, well-behaved function that can describe – more or less successfully – the behavior of an electron in an atom" (and similarly for an MO). For some students, an AO was understood as or connected with "a region in space inside which there exists a given probability, for example 90 %, for an electron to be encountered."

Also, a significant proportion of the students identified an MO only with a linear combination of AOs. Confusion causes the fact that the actual solutions of the Schrödinger equation for the hydrogen and hydrogen-like atoms are complex functions, except for the *s*-type orbitals. Impressive was the misinterpretation of the figure eight "*p*-type AO," familiar from previous instruction – this is a cross section of the graph of the squared spherical harmonic, $Y^2(\theta, \varphi)$, for the p_z AO; it *does not* give the shape of a p_z orbital. Very few students recognized the *equal probability contour* (or *boundary surface*) for a p_y orbital.

In many-electron atoms, the Schrödinger equation cannot be solved exactly, so approximations must be made. The simplest and crudest approximation is to neglect entirely electron-electron interactions (repulsions) and electron spin. In this way, hydrogenic orbitals are found as solutions. Into these orbitals the electrons are placed, according to the *Aufbau principle*, resulting in *electron configurations*. More sophisticated methods are available that take into account, in an approximate fashion, the electron-electron interactions. All these involved "details" do not become knowledge for many students. The concept of Slater determinants, their definition, and the approximations involved also caused difficulties. The same was the case with the concepts of spectroscopic terms. On the other hand, the algorithmic processes of writing all *Slater determinants* arising from a given electron configuration or of finding the *term symbols* for a given configuration were easy tasks for most students.

Study II: Twelfth-Grade Students' Conceptual Difficulties

In a preliminary quantitative study (Tsaparlis and Papaphotis 2002), we exposed 12th-grade Greek students to a number of questions that differed from the standard simple recall or application/algorithmic questions set in the examinations, which have been practiced by the students (Study II). The questions were intended to test for deep understanding and critical thinking.

The subjects of the study were 119 students from upper secondary schools plus 62 first-year biotechnology undergraduate students at the very beginning of their university studies. All students had the same background in the quantum chemical concepts from their school course. The high school students were preparing for their university entrance examinations, in which achievement is crucial for the students' selection for higher education, so they had to study seriously and hard. The undergraduate students were among the relatively high achievers in the university entrance examinations.

The findings indicated that many students thought in terms of old quantum theory, assuming that the term "orbital" is another word for an "orbit," and that the electrons rotate around the nucleus like the planets around the sun. In addition, a number of them considered that orbitals are unique and represent a well-bound fixed space. Many students failed to realize the probabilistic nature of AOs, subscribing to a deterministic perspective. In addition, students had the misconception that the hydrogen-like orbitals are as exact for many-electron atoms as they are for the one-electron case.

Study III: Conceptual Versus Algorithmic Learning

Studies III and *IV* extended the work of *Study II*, in three ways: first, a more selective sample of students was used; secondly, we maintained from the previous questionnaire a number of questions that were found to be more relevant and interesting but also added new ones; and thirdly, in addition to the conceptual questions that require for their answer conceptual understanding and/or critical thinking (*type C* questions), we included a number of questions that require just recall of knowledge or the application of known and well-practiced algorithms (*type A* questions).

Conceptual questions have been associated with Ausubel's meaningful learning (Ausubel 1968, 2000; Ausubel et al. 1978). Meaningful learning is "considered qualitatively different from rote learning in terms of non-arbitrary and non-verbatim reproduction of the content that is to be learnt to existing ideas in cognitive structure" (Ausubel 2000, p. 40). It "requires well-organized relevant knowledge structure and high commitment to seek relationships between new and existing knowledge." On the other hand, algorithmic questions might be answered by employing only rote learning. "Rote learning results from little relevant knowledge poorly organized and little or no commitment to integrate new with existing relevant knowledge" (Novak 2002, p. 551).

From a different perspective, conceptual questions require what has been termed as higher-order cognitive skills (HOCS), while algorithmic questions can be answered by employing lower-order cognitive skills (LOCS) (Zoller 1993). According to Zoller and Tsaparlis (1997, p. 118) (see also Zoller et al. 1995, p. 987), HOCS items include "quantitative problems or conceptual questions unfamiliar to the student, that require more than knowledge and application of known algorithms; they require analysis, synthesis, and problem solving capabilities, the making of connections, and critical evaluative thinking". HOCS should be contrasted to LOCS "that require simple recall of information or a simple application of known theory or knowledge to familiar situations and context; they can also be problems (mostly computational exercises) solvable by means of algorithmic procedures (algorithms), already familiar to the learner through previous specific directives or practice or both."

Many chemistry teachers assume that the ability to apply algorithmic-taught procedures for solving a problem (an exercise) or for executing a given task, for instance, constructing electron configurations of atoms by placing electrons in AOs, is equivalent to conceptual understanding of chemistry. Extensive research has shown that the ability to apply algorithms does not presuppose conceptual understanding (Stamovlasis et al. 2004, 2005, and references therein). Of particular interest is the categorization of students by Nakhleh (1993) into four categories according to their performance in the two types of questions: (1) algorithmic high, conceptual high (A1C1); (2) algorithmic high, conceptual low (A1C0); (3) algorithmic low, conceptual high (A0C1); and (4) algorithmic low, conceptual low (A0C0).

Our aims have been, on the one hand, to make a comparison between their performance in the two types of questions (*Study III*, Papaphotis and Tsaparlis 2008a) and, on the other hand, to explore further students' conceptual understanding of basic quantum chemical concepts (*Study IV*, Papaphotis and Tsaparlis 2008b).

Study III was a quantitative one and involved 125 first-year students at the start of their courses, from three Greek university departments, chemistry, biotechnologies, and material science (Papaphotis and Tsaparlis 2008a). The study tested the relevant knowledge that these students had acquired in high school. A written questionnaire consisting of 14 questions was used. Five of these were type A, and nine were type C questions. Performance in the type A questions was relatively high, ranging from 59.2 to 74.4 %. Performance in the type C questions was generally much lower, ranging from 11.6 to 37.5 %. The following were the research questions posed:

1. To what extent is the postulated categorization of questions (conceptual versus algorithmic) supported by the data?
2. To what extent is competence in applying algorithms connected with competence in conceptual understanding (and vice versa)?
3. How are students distributed into the four categories of the Nakhleh categorization?

The answers to the above research questions were as follows:

1. *Conceptual versus algorithmic questions*. Principal component analysis (PCA) classified the questions in agreement with their type, A or C.
2. *Competence in applying algorithms versus competence in conceptual understanding* (*and vice versa*). The findings supported the independence between the conceptual and the algorithmic dimension, implying that the algorithmic behavior does not presuppose conceptual understanding, and vice versa.
3. *The Nakhleh categorization*. A large portion of the students (36.8 %) exhibited only algorithmic behavior, while fewer students exhibited both abilities (6.4 %) or only the conceptual one (3.2 %).

The general conclusion was that competence in applying algorithms may be independent of competence in conceptual questions, that is, the algorithmic behavior does not presuppose conceptual understanding, and vice versa. The main problem then lies with an acceptable understanding of the basic quantum chemical concepts.

Study IV: Students' Difficulties and Misconceptions with Current Structural Models

As mentioned above, *Study IV* is derived from the same data as *Study III* (Papaphotis and Tsaparlis 2008b). The research questions were as follows:

1. What errors are made by the students in answering questions that deal with simple recall of knowledge or straightforward application of algorithms?
2. What are the patterns of performance, the misconceptions, and the main difficulties that characterize the students when they have to deal with questions that require conceptual understanding and/or critical thinking?

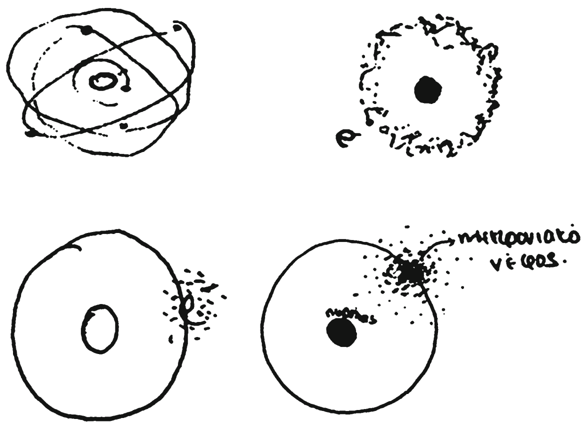


Fig. 1 Indicative drawings/answers to question C5. (The comment "electron cloud" in Greek has been added in the fourth drawing.) (Papaphotis and Tsaparlis 2008b – Reprinted with permission of the Royal Society of Chemistry)

A considerable proportion of students (65 %) provided acceptable answers to a knowledge (type A) question about how in the shapes of the orbitals it is shown or should be shown that "the exact size of the orbitals is impossible to show, since we have said the probability of finding the electron does not become zero even at long distances from the nucleus." In most unacceptable answers, reference was made just to the electron cloud, without further elaboration. In a relevant conceptual question, students were asked to spot an error in either or in both of the pictures shown in the question. Acceptable answers dropped to 38 %.

In another conceptual question, students were asked how it would be possible to construct the picture of the electron cloud, by using transparent photos of the electron as it moves around the nucleus: "I would take many photos of the electron printed on transparent paper, and then I would superimpose all these photos." The acceptable answers were few (13 %). A very large part of the unacceptable answers followed (in descriptions or in drawings) the Bohr/deterministic model; some of them made a combination (hybrid model) of the quantum mechanical (electron cloud) with the deterministic model, drawing an orbiting electron cloud or a flattened/spread-out orbit (see Fig. 1).

Very low was the performance in a conceptual question that asked students to make a drawing depicting the hydrogen atom as one imagines it is in reality: probabilistic answers 16 % and deterministic answers 72 %. In most unacceptable answers, students made a (probabilistic or deterministic) drawing of the hydrogen molecule. Over two thirds of the students adhered to the planetary model. Figure 2 shows representative student drawings.

A conceptual question asked if it is possible for the electron of the ground-state hydrogen atom to be found outside the space that is defined as 1s orbital. The acceptable answers were low again (14 %). Most of the unacceptable answers referred or implied that the electron could be found outside the "1s space" only if it were excited. Such answers represent deterministic views of the orbital, assuming it as a fixed space.

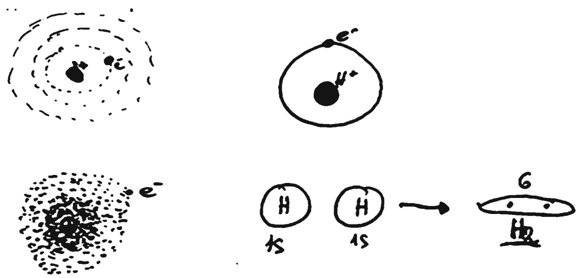


Fig. 2 Representative student drawings for a hydrogen atom (Papaphotis and Tsaparlis 2008b – Reprinted with permission of the Royal Society of Chemistry)

Finally, a conceptual question dealt with the formation of an MO by the combination overlap of two AOs. Acceptable answers were provided by 21 % of the students. The idea of subtraction of orbitals appeared strange to many students. To them, subtraction of spaces results in a smaller space, hence an increased electron density and a strengthening (instead of weakening) of the bond. Other students invoked energy arguments, often with subtraction involving very high energy changes hence practically infeasible.

Study V: Students' Levels of Explanations, Models, and Misconceptions

Science has as its ultimate goal "to produce viable explanations for phenomena" (Driver et al. 1996, p. 44). To do this, it constructs and uses a wide variety of models and theories. Focusing on education, scientific explanations need to be meaningful, illustrative, and adapted to the students (Mortimer and Scott 2003; Ogborn et al. 1996; Scott et al. 2006; Taber and Watts 2000). Within the alternative conceptions perspective, explanations are distinguished into *true explanations* and *pseudo-explanations*, with true explanations being either *scientific* or *alternative explanations* (Taber and Watts 2000).

In *Study V*, we investigated beginning undergraduate chemistry students' explanations and models about basic quantum chemistry concepts and placed the explanations and models in the meaningful-learning/rote-learning continuum (Stefani and Tsaparlis 2009). Our ultimate aim was to check whether chemistry students have a deep understanding, consistent with Ausubel's meaningful learning (Ausubel 1968, 2000; Ausubel et al. 1978). Novak (2002) has shown how meaningful learning and the transfer of knowledge relate. Both rote/meaningful and reception/discovery dimensions of learning exist on a continuum rather than being dichotomous in nature.

The research questions of *Study V* were as follows:

1. Were propositional claims and/or causality included in students' explanations?
2. What was the variation in students' explanations according to the above [in (1)] two criteria?
3. What was the variation in students' notions of models?

4. What was the interpretation of combined levels of explanations with levels of models with respect to the meaningful-/rote-learning continuum?
5. What misconceptions were apparent?

The subjects were 19 second-year students (10 female and 9 male) from the Department of Chemistry of a Greek university (mean age ~19.5 years). None of the students had received any prior quantum chemistry instruction in secondary education. They had encountered the relevant quantum chemistry concepts in a number of inorganic and organic courses but mainly in the introductory inorganic course. Eight of the nineteen students had also been taught a chapter on quantum chemistry within an elementary physical chemistry course. As criterion for selecting the students, we used their passing of the introductory inorganic and the elementary physical chemistry courses, but they had also passed additional courses. As a result, the selected students were among the best attending and best performing in their studies.

The following topics were questioned in the interviews: (1) AOs (definition, pictorial representation, types), (2) the Schrödinger equation (equation classification/systems of application), (3) the hydrogen atom versus the helium atom (exact solution versus zero-order approximation), (4) the oxygen atom (zero-order approximation), (5) MOs, (6) hybrid orbitals, and (7) ionic and covalent bonding.

The method of analysis followed the conventions of *phenomenography*. This method does not focus on the individuals but searches instead for variation in student understanding about phenomena (Marton 1981).

The Levels of Explanations. Four levels of explanation in the students' answers were identified: (*a*) verbatim reproduction of textbook knowledge; (*b*) in addition to words and terms from the textbook, inclusion of lower-quality propositional claims; (*c*) reproduced textbook knowledge, also implying causality; and (*d*) implication of causality, including claims used for making explanations that indicate higher-level thinking.

The Levels of Models. The study identified also three levels of models: (*1*) models as replicas of reality; (*2*) models as useful scientific constructions, but with the emphasis still on reality; (*3*) models as powerful instruments for explaining the physical world.

Finally, the combination of levels of explanations, with levels of models, led to four categories, with categories *A* and *B* in the rote-learning part of the rote-learning/meaningful-learning continuum and categories *C* and *D* in the meaningful-learning part. Students of categories *A* and *B* relied on memorizing and reproducing some content, possessed a naïve view of models, and were limited to a rigid content of poor explanatory power. Students of categories *C* and *D* gave successful explanations that indicated an in-depth scientific knowledge, close to that of experts.

Study VI: Attempts at Conceptual Change

Numerous studies have shown that conceptual change is very hard to accomplish. Concepts deeply rooted in students' mental images are difficult to replace by other models, strongly resisting change, even if the knowledge presented is logical, and well-thought out, carefully planned, and implemented teaching strategies are used. Further, students, even if they come close to realizing the errors in their established thinking, revert very easily to their previous ideas, with which they are more comfortable (Driver 1983; Eylon and Linn 1988).

The work which has been reviewed so far was of a diagnostic character. *Study VI* attempted to achieve conceptual change in students (Tsaparlis and Papaphotis 2009). We employed active learning methods of teaching and learning, with students working under the instructor's observation and guidance but more effectively by students working together in small groups to accomplish an assigned common learning task/goal. Research evidence supports that these discursive approaches to learning provide a better learning environment and contribute to deeper understanding and development of learning skills (Duncan-Hewitt et al. 1995; Johnson et al. 1991; Stamovlasis et al. 2006). Active and cooperative learning methods are consistent with *social-cultural constructivism* (Vygotsky 1962).

On the basis of the 125 students' performance in the written questionnaire of *Studies III* and *IV*, 23 selected students took part in semi-structured interviews. Among them there were students with an overall satisfactory performance, students with good performance in recall-algorithmic questions but not so good in the conceptual questions, and vice versa. The interviews were individual and in groups of three or four. In the interviews, we dealt only with conceptual questions that referred to the deterministic or probabilistic conceptual interpretation of basic quantum chemical concepts and principles.

The aim of our intervention was the change of students' ideas into modern (probabilistic, quantum mechanical) views. The change was found to be statistically significant for the nature of the orbitals and the atomic model, but not for the uncertainty principle. A large number of students had not understood the fundamental nature of the Heisenberg principle, considering instruments or the measurement procedures or both as responsible for the uncertainty deriving from the Heisenberg principle. Consequently, "it is a matter of time for man to achieve precise measurements in the micro world." Other students who had been categorized as rote learners reproduced verbatim what is written in the books and arrived at an acceptable answer.

The planetary Bohr model, which is taught in earlier education and is most often encountered in books, remained strong in many students' minds. Some of the students insisted on the planetary model but accepted elliptic orbits in addition to circular ones or spread-out orbits. Other students were mixing ideas from the planetary model, representing the hydrogen atom with a delineating curve, thus mixing orbitals and orbits. Even if many students knew the concept of the electron cloud, they did not accept that it provides a picture of the atom. The analogy of electron's movement with the appearance of the spokes of a fast rotating bike's wheel proved effective. A hybrid model was also the common replacement of the representation of the electron as a dot or small circle with a small electron cloud/packet that moves again on specific orbits (see Fig. 1).

Many students found it difficult to understand the probabilistic nature of the orbital concept. In addition, they identified the orbital only with the fixed space enclosed (or only its surface) by the orbital shape used, that is, the shape of the orbital that refers to a certain probability. It is useful to emphasize that the particular envelope that is "fixing the orbital" and we are interested in is the one which includes this probability distribution in a minimum volume. In pictures of the electron cloud, those dots that were outside the circle that was drawn to "define the orbital" were assumed in several cases to belong to other (excited) orbitals. An effective approach to conceptual change was through the change of orbital size with the value of probability to encounter the electron.

The mathematical description of the formation of MOs by means of linear combinations of AOs caused no problems in the case of constructive (bonding) addition, but was very problematic in the case of destructive (antibonding) subtraction. While there were several students who made a correct judgment, many students encountered great difficulty with understanding and accepting the subtraction of AOs. Even in cases of logically correct answers, they were uncertain if that could happen in practice or if that had simply to do with a mathematical artifact. The main obstacle to accepting the subtraction is the way they have built the orbital concept, assuming it as "space" and not as mathematical function. For some students, addition, hence bond formation, should be preferred by nature. Another misconception was that of the two nuclei moving apart from each other (separating) as a result of AO subtraction. Also, that if the overlapping orbitals were identical (e.g., both 1s), bond breaking would result, but if they were different (e.g., 1s and 2s), the result would be bond weakening. Finally, the use of pictures of electron clouds seemed to facilitate understanding of the addition but not of the subtraction of orbitals.

As expected, the students who performed well in the conceptual questions of the written questionnaire gave "good" answers during the interviews, although they often encountered conceptual difficulties. Also, students with moderate or low performance in these questions often made useful, constructive, and interesting contributions. The net conclusion is that the methodology used can be useful for all students, irrespective of their behavior in traditional written exams.

Conclusions

In our studies, we analyzed students' examination papers, written answers to questionnaires, or discussed with the students their views on the abstract quantum concepts. We focused on the ideas they expressed about the theoretical descriptions of non-observable entities and the connections they made between non-observables and reality. The findings point at three main problems in the learning of the basic quantum chemistry concepts by high school and freshmen university students: (a) the insistence on the deterministic models of the atom derived from old quantum theory; (b) the misinterpretation of models and theories and the poor understanding of the modern quantum concepts, including their mathematical features; and (c) the formation of misunderstandings and misconceptions.

More specifically, *Study I* found that chemistry graduates do not have a deep and precise understanding of modern concepts of AOs, MOs, and related concepts.

For instance, most students failed to provide a mathematical definition for an AO or an MO or to realize that hydrogenic orbitals are only gross approximations for many-electron atoms. These knowledge deficiencies result from the fact that the introductory courses treat orbital ideas only in terms of regions of space around the nucleus with a given probability of finding electrons of an atom.

In *Studies II through IV*, twelfth-grade students were exposed to conceptual questions that differed from the standard simple recall or application/algorithmic questions set in the examinations. Studies III and IV included also the usual and familiar to the students recall of knowledge and algorithmic-type questions. Principal component analysis (PCA) confirmed such a classification. The algorithmic behavior does not presuppose conceptual understanding, and vice versa. *Study IV* (derived from the same data as *Study III*) spotted errors made by the students in the simple recall and algorithmic questions and identified patterns of performance, misconceptions, and the main student difficulties when dealing with the conceptual questions. Performance dropped usually dramatically when dealing with the latter questions.

Using the method of phenomenography, *Study V* investigated beginning undergraduate chemistry students' explanations and models about the following quantum chemistry concepts: AOs, the Schrödinger equation, the hydrogen atom versus the helium atom, the oxygen atom, MOs, hybrid orbitals, and ionic and covalent bonding. The study used Ausubel's theory of meaningful learning and placed the explanations and models in the meaningful-learning/rote-learning continuum. Four levels of explanations and three levels of models were identified. The combination of levels of explanations with levels of models led to four categories, with categories *A* and *B* in the rote-learning part of the rote-learning/meaningful-learning continuum and categories C and D in the meaningful-learning part.

Study VI employed active learning methods of teaching and learning with the aim to achieve conceptual change. Students were interviewed individually or worked together in small groups under the instructor's observation and guidance. Conceptual questions (which were about the deterministic or probabilistic conceptual interpretation of basic quantum chemical concepts and principles) aimed to change students' ideas into modern (probabilistic, quantum mechanical) views. The methodology used proved useful for all students, irrespective of their behavior in traditional written exams. Despite this optimistic message, a limitation of the study should be made clear: we do not know if this is a meaningful change and if the students who changed their view will revert back when questioned at a later time in a different context. Further research is necessary here.

Discussion, Implications, and Recommendations for Learning and Teaching

The concepts and processes of quantum chemistry are abstract and complex, so learning is difficult without a thorough understanding of the subject, without meaningful learning. The following dialogue between the investigator (I) and a new graduate chemistry student (S) demonstrates this (Tsaparlis, unpublished results):

I: Is there, however, something that is beyond the instructors? That is, features of the subject [quantum chemistry]?

S: *Yes, the concepts of orbitals are, I think, more difficult, that is, personally I had a larger problem with them.*

I: Why?

S: *I don't know, I couldn't understand them, there was a problem.*

Conceptual understanding requires *meaningful learning* and the ability to employ *higher-order cognitive skills*. If students fail to achieve conceptual understanding, they have to resort to rote learning of definitions, formulas, and processes, which requires the use of lower-order cognitive skills.

The mathematical character of quantum chemistry (such as the use of operators) is an added factor of difficulty. A new chemistry graduate student commented: "Surely the concepts and the mathematical formulas [of quantum chemistry] are difficult. They do not make the relevant concepts understandable. That is, they are based more on mathematical reasoning than (physical) arguments" (Tsaparlis, unpublished results). The mathematical complexity has led even many practicing chemistry researchers to have adopted a quasi-quantum character to the quantum chemistry tools they employ in their practice (Sánchez Gómez and Martín 2003). This is in line with Linus Pauling's comment that "only in a few cases have results of direct chemical interest been obtained by the accurate solution of the Schrödinger wave equation… The principal contribution of quantum mechanics to chemistry has been the suggestion of new ideas, such as the resonance of molecules among several electronic structures with an accompanying increase in stability" (Pauling 1938, preface). Practical quantum chemistry is indeed based on using approximate methods. "(A)tomic orbitals can no longer be said to physically 'exist' in anything except one electron systems. Many-electron orbitals are ontologically redundant" (Scerri 2001, p. 167). One has to admit, however, that numerical/computational quantum chemistry has now achieved a high accuracy level and is indispensable in modern chemical research.

In their recent book about the history of quantum chemistry, Gavroglu and Simões (2012) have considered the resistance of chemists to include mathematics and physics to understand quantum chemistry by invoking L. Pauling, G. N. Lewis, and C. A. Coulson. As early as 1923, Lewis emphasized the need for chemists to master the laws of physics in order to understand the electron pair bond ("the cardinal phenomenon of all chemistry") (Lewis 1923, pp. 132–133). In his *The Nature of the Chemical Bond*, Pauling stressed the use of quantum mechanics in order to understand the chemical bond but kept mathematical formalism to a minimum, appealing to "chemists' intuition" and experimental data. For Coulson, the major contribution of quantum mechanics was not to have provided its mathematical theory but rather to facilitate insight and understanding at a deeper level. Coulson consistently demonstrated that the mathematization of quantum chemistry and its visual expressions were not incompatible defining characteristics.

I am convinced that without any mathematics, it is not possible to arrive even at an elementary understanding of the concepts and avoid or cure misconceptions. However, it could be argued that the quantum chemistry concepts can be understood at an acceptable level with only a minimal mathematical treatment, using mathematical equations and functions but without the need to solve differential equations or performing other complicated mathematical operations. In any case, the underlying physical picture and its connections with mathematics should be emphasized. Conceptual meaningful learning should always be the main instructional target.

Quantum Chemical Concepts in High School and in General Chemistry

The presentation in early school chemistry courses of the ideas and concepts of the old quantum theory is questionable. Alternative ways exist that while avoiding the orbitals, do not use models such as the Bohr atom and the octet rule. Johnstone et al. (1981) have treated bonding this way by developing the concept of electrons trying to keep as far apart as possible. Gold (1988) concluded that concepts such as quantum numbers and orbital shapes are too abstract for high school chemistry students. Gillespie contended that more emphasis should be placed on electron density rather than on orbitals; Lewis structures and VSEPR are all that is required for high school, while the electron-domain model is sufficient for general chemistry (Gillespie and Matta 2001).

Niaz and Femández (2008) evaluated 55 freshman college-level general chemistry textbooks and reported, among others, that: none of the textbooks presented a framework to facilitate transition in student understanding from classical to quantum mechanics; few textbooks facilitated the introduction of quantum numbers based on experimental determination of electron density (photoelectron spectrum); none of the textbooks described satisfactorily that orbitals are mathematical constructs, and the shapes of the orbitals can be derived from electron density measurements. According to the authors, the inclusion of such criteria in textbooks can facilitate students' conceptual understanding of quantum numbers and electron configurations.

In any case, if high school and introductory college chemistry courses and textbooks are to treat quantum chemistry concepts at all, they should do it with great care, emphasizing their underlying physical picture (especially their probabilistic character) and the connection with mathematics. In my opinion, the following is a minimal list of theoretical facts that (as a rule) are related to the findings of our studies and should form the basis for leading students into conceptual understanding and meaningful learning of the basic quantum chemical concepts and models:

- Quantum mechanics has a probabilistic (in contrast to deterministic) nature.
- The mathematical meaning and a definition of AOs as functions/solutions of the Schrödinger equation of the hydrogen atom should be introduced first.
- Various graphical representations of these functions provide then physical meaning to the AOs by relating them to electron probabilities or equivalently to electron densities. Particular emphasis should be placed on sections of contours of equal probability.

- Molecular-orbital theory, which is based on Linear Combinations of AOs (LCAO), is also a mathematical model, while constructing MO shapes by combining AO shapes is again a graphical representation of mathematical functions.

Misconceptions and Conceptual Change

The problem of misconceptions is serious. Misconceptions appear to arise partly from textbooks and instruction and partly from the very nature of quantum theory (Bodner 1991; Fishler and Lichtfeldt 1992; Kalkanis et al. 2003; Tsaparlis and Papaphotis 2002) and from *epistemological obstacles* to the acquisition of quantum mechanical knowledge (Kalkanis et al. 2003). It is needless to say that it might be difficult to overcome the problems with traditional didactic teaching methodology, for it may be that more and better content, taught in the old didactic way, is very unlikely to improve the situation (Stofflett and Stoddart 1994).

Taber (2001) has identified key "pedagogic impediments" ("alternative aspects of learners' thinking that seem to derive from the way the subject is taught") and made practical suggestions about revised teaching that could help learners construct the scientific models rather than develop the alternative conceptions. Kalkanis et al. (2003) proposed an educational strategy for a simple, qualitative, and sufficient approach to quantum mechanics by prospective teachers. The strategy aims at a conceptual structure that includes classical and quantum physics as two totally independent systems. The complete distinction of the two systems demands a radical reconstruction of students' initial knowledge that is based on the juxtaposition of the two models. Greca and Freire (2003) have chosen a didactic strategy that puts the emphasis on the quantum features of the systems, instead of searching for classical analogies. In particular, the method considers the concept of quantum state as the key concept of quantum theory, representing the physical reality of the system, independent of measurement processes. More than half of students involved in the implementation of the strategy attained a reasonable understanding of the basics of quantum mechanics. Nakiboğlu (2008) used a word association test and found that instruction produced a significant difference: the orbital concept appeared at the highest frequency level and joined to the electron concept; at the weakest level, the other concepts related to the quantum mechanical model of the atom, such as quantum numbers, principal quantum number, and the name of orbital types, appeared in the network.

In science there exist often two (or more) competing (theoretical) models. "Then the key activity of scientists is evaluating which of these alternatives … presents the most convincing explanation for particular phenomena in the world" (Driver et al. 2000, p. 296). When models are in conflict one with another, students choose to adopt the one that seems more concrete to them and for this reason seems more reasonable (Taber 2002a). An effort to remove the popular models totally from students' minds is not an easy task, so it must be made clear to the students, especially at the tertiary level, that, although limited in explanatory power, they are still used in explaining some aspects of the phenomena under discussion because they are simple and easy to manipulate (Van Driel and Verlop 1999).

Conceptual change pedagogy applied in instructional practice (and which is still missing at least from chemistry texts (Shiland 1997)) holds promise of being effective in overcoming to a certain extent deterministic views and misconceptions about quantum chemical concepts (Tsaparlis and Papaphotis 2009). Our study on conceptual change (*Study VI*) confirmed that the active and cooperative methods of teaching and learning employed provided a better learning environment and contributed to deeper understanding and development of learning skills. Our method can be considered within Mortimer and Scott's (2003) communicative approach, which categorizes the teacher-student classroom communication into four classes: (1) interactive and dialogic, (2) noninteractive and dialogic, (3) interactive and authoritative, and (4) noninteractive and authoritative.

The use of computers, in particular, the use of models, simulations, and animations, may also help high school students contradict and overcome the relevant misconceptions. However, not all available software is effective. In a study with 20 first-year primary education students in Greece, the students interacted with two Internet-based software packages that used three-dimensional visualizations of the quantum atomic model (Kontogeorgiou et al. 2007). The findings indicated that the visualizations did not help students to understand the relevant scientific concepts and the atomic shape. The authors proposed instead the use of Virtual Reality Technologies for the creation of atomic visualizations based on scientific data that support conceptual change.

The Quantum Chemistry Course

The undergraduate quantum chemistry course should aim that the students understand basic principles of quantum mechanics,[1] introduce approximate methods, and perform electronic structure calculations at different levels of theory. The intended learning outcomes should be that students should be able to use quantum mechanics in practice: molecular nuclear motion and electronic structure calculations. The teaching and learning activities should include lectures, workshops, and colloquia; problem solving classes, computational exercises; and student-centered learning (The *Advanced Spectroscopy in Chemistry* (ASC) *Master*, http://www.master-asc.org/asc_master/?c=1&p=39, accessed 20 April 2013).

[1] A feature of most introductions to quantum chemistry is their postulative approach. Although the Schrödinger equation cannot be proved or derived strictly, there are many ways to introduce this equation that provide insights into the meaning of quantum mechanics. I have suggested an approach from the historical perspective, in which I first study the methods of the pioneers Schrödinger, Heisenberg, and Dirac. Following that, I made a synthesis of various modern heuristic treatments into a coherent and meaningful whole (Tsaparlis 2001).

Educational research and experience show that the emphasis in the undergraduate quantum chemistry course should be shifted from the complicated mathematical operations and derivations to the deep understanding of the concepts. Gardner and Bodner (2008) found that many of the problems that undergraduate chemistry and physics students enrolled in introductory chemistry and physics courses encountered were the result of the nonproductive approach and strategies the students were called to employ.

Despite limitations that are a consequence of the inherent nature of learning, constructivist pedagogy that employs active and cooperative forms of learning, and aims at *conceptual conflict* and *conceptual change*, holds the promise of being more effective in diminishing or in overcoming misunderstandings and misconceptions. To this end, special techniques can be effective, such as *integration* (which attempts to link concepts, e.g., AOs, hybrid orbitals, and MOs) and *differentiation* (which aims at identifying differences between related concepts, e.g., between hydrogenic and non-hydrogenic orbitals or between AOs and MOs) (Hewson and Hewson 1984).

Last but not least, modern computational quantum chemistry and the applications to experimental chemistry (e.g., spectroscopy and lasers) are expected to motivate students to learn the theory and the methods of quantum chemistry. According to Fong (1962, p. 47), "It is the successes of quantum mechanics in (numerous) applications that justify its basic assumptions and establish its validity." Being aware of the fact that instructors should be very selective and careful in their use of new educational technologies in education, we believe that computers may contribute to better teaching and learning in undergraduate education. The *Digital Library for Physical Chemistry* of the *Journal of Chemical Education* (Ziellinski 2005) includes instructional resources that span the physical chemistry curriculum. For instance, "Quantum states of atoms and molecules" is an introduction to quantum mechanics applied to spectroscopy, the electronic structure of atoms and molecules, and molecular properties (Ziellinski 2005).

Concluding Comments

The process of science from "real objects" to "theoretical objects" is described by Matthews (2007) with four levels: Level 4 involves the events and processes in the real world (the "real objects" of science); Level 3 has the observations and the measurements of discreet events in the real world (the data); Level 2 represents phenomena by models (the theoretical objects of science); and finally, Level 1 contains the scientific laws and high-level theory.

Up to the nineteenth century, classical physics was based on *scientific realism* that had remained compatible with the naïve realism of everyday thinking. However, the advent of quantum theory at the beginning of the twentieth century made it impossible to visualize the world in terms of ideas of the everyday world (Wikipedia, Naïve realism). "We have no satisfactory reason for ascribing objective existence to physical quantities as distinguished from the numbers obtained when we make the measurements which we correlate with them. There is no real reason for supposing that a particle has at every moment a definite, but unknown, position which may be revealed by a measurement of the right kind… On the contrary, we get into a maze of contradiction as soon as we inject into quantum mechanics such concepts as carried over from the language and philosophy of our ancestors… It would be more exact if we spoke of 'making measurements' of this, that, or the other type instead of saying that we measure this, that, or the other 'physical quantity'" (Kemble 1937, p. 244). "The general conclusion is that in quantum theory naïve realism, although necessary at the level of observations, fails at the microscopic level" (Gomatam 2004, p. 2).

AOs, MOs, and related concepts derive from Schrödinger's wave mechanics, which is an approximation to nature (a model). "Orbital concepts are merely aspects of the best presently available model; they are not 'real' in the same sense that experimental observations are" (Simons 1991, p. 132). Dirac's relativistic quantum mechanics (which takes the theory of relativity into account) is a better model that explains experimental observations which the Schrödinger model does not (McKelvey 1983).

Learning about science and the process of science is an evolutionary process that does not occur simultaneously among all students. Science educators argue that to acquire scientific concepts, students have to be exposed to the concepts over an extended period of time. As a consequence, the findings that were described in this review and the comments and recommendations made should not imply that the only reasonable outcome from instruction should be perfect understanding, with no lingering misconceptions (*zero-error tolerance*). In addition, I should emphasize that sometimes we take for granted that our students "see" the same things and that words "mean the same thing" to them as they do to us. This is far from true. I would then encourage educators to critically think about what words, images, representations, and resources they use in their teaching and how they might and do impact their students' understanding. This type of attention will keep educators aware of their own missteps in word choice or in image use and interpretations.

References

Ausubel, D. P. (1968). *Educational psychology – A cognitive view*. New York: Holt, Reinhart & Winston.

Ausubel, D. P. (2000). *The acquisition and retention of knowledge: A cognitive view*. Dordrecht: Kluwer.

Ausubel, D. P., Novak, J. D., & Hanesian, H. (1978). *Educational psychology – A cognitive view*. New York: Holt, Reinhart & Winston.

Bodner, G. M. (1991). I have found you an argument – The conceptual knowledge of beginning chemistry graduate students. *Journal of Chemical Education, 68*, 385–388.

Borkoff, G., & von Newmann, J. (1936). The logic of quantum mechanics. *Annals of Mathematics, 37*, 835–843.

Castro, E. A., & Fernandez, F. M. (1987). Intellectual development beyond formal operations. *International Journal of Science Education, 9*, 441–447.

Coll, R. K., & Taylor, N. (2002). Mental models in chemistry: Senior chemistry students mental models of chemical bonding. *Chemistry Education Research and Practice, 3*, 175–184.

Coll, R. K., & Treagust, D. F. (2001). Learners' mental models of chemical bonding. *Research in Science Education, 31*, 357–382.

Coll, R. K., & Treagust, D. F. (2002). Exploring tertiary students' understanding of covalent bonding. *Research in Science and Technological Education, 20*, 241–267.

Coulson, C. A. (1974). Mathematics in modern chemistry. *Chemistry in Britain, 10*, 16–18.

Dirac, P. (1929). Quantum mechanics of many-electron systems. *Proceedings of the Royal Society of London, A123*, 714–733.

DiSessa, A. (1988). Knowledge in pieces. In G. Formn & P. B. Pufall (Eds.), *Constructivism in the computer age* (pp. 49–70). Hillsdale: Erlbaum.

Driver, R. (1983). *The pupil as scientist?* Milton Keynes: Open University Press.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young people's image of science*. Buckingham: Oxford University Press.

Driver, R., Newton, P., & Osborne, J. (2000). Establishing the norms of scientific argumentation in classrooms. *Science Education, 84*, 287–312.

Duncan-Hewitt, W., Mount, D. L., & Apple, D. A. (1995). *A handbook on cooperative learning* (2nd ed.). Corvallis: Pacific Crest.

Eylon, B.-S., & Linn, M. C. (1988). Learning and instruction: An examination of four research perspectives in science education. *Review of Educational Research, 58*, 251–301.

Fishler, H., & Lichtfeldt, M. (1992). Modern physics and students' conceptions. *International Journal of Science Education, 14*, 181–190.

Fong, P. (1962). *Elementary quantum mechanics*. Reading: Addison-Wesley.

Franco, C., Lins de Barros, H., Colinvaux, D., Krapas, S., Queiroz, G., & Alves, F. (1999). From scientists' and inventors' minds to some scientific and technological products: Relationship between theories, models, mental models, and conceptions. *International Journal of Science Education, 21*, 277–291.

Gardner, D. E., & Bodner, G. M. (2008). Existence of a problem-solving mindset among students taking quantum mechanics and its implications. In M. D. Ellison & T. A. Schoolcraft (Eds.), *Advances in teaching physical chemistry* (pp. 155–173). Washington, DC: American Chemical Society/Oxford University Press.

Gavroglu, K., & Simões, A. (2012). *Neither physics nor chemistry: A history of quantum chemistry*. Cambridge, MA: Massachusetts Institute of Technology Press.

Gillespie, R. J., & Matta, C. F. (2001). Teaching the VSEPR model and electron densities. *Chemistry Education Research and Practice, 2*, 73–90.

Gold, M. (1988). Chemical education: An obsession with content. *Journal of Chemical Education, 65*, 780–781.

Gomatam, R. (2004). Physics and commonsense – Reassessing the connection in the light of the quantum theory. http://arxiv.org/ftp/arxiv/papers/0708/0708.1536.pdf. Accessed 20 April 2013.

Greca, I. M., & Freire, O., Jr. (2003). Does an emphasis on the concept of quantum states enhance students' understanding of quantum mechanics? *Science Education, 12*, 541–557.

Halloun, I. A. (2007). Mediated modeling in science education. *Science Education, 16*, 653–697.

Harrison, A. G., & Treagust, D. F. (2000). Learning about atoms, molecules, and chemical bonds: A case study of multiple-model use in grade 11 chemistry. *Science Education, 84*, 352–381.

Hewson, W. H., & Hewson, M. G. A. (1984). The role of conceptual conflict in conceptual change and the design of science instruction. *Instructional Science, 13*, 1–13.

Ireson, G. (2001). On the quantum thinking of physics undergraduates. In H. Behrendt, H. Dahncke, R. Duit, W. Graber, M. Komorek, A. Kross, & P. Reiska (Eds.), *Research in science education – Past, present, and future* (pp. 83–88). Dordrecht: Kluwer.

Johnson, D. W., Johnson, R. T., & Smith, K. A. (1991). *Active learning cooperation in the learning classroom*. Edina: Interaction Book Co.

Johnstone, A. H., Morrison, T. I., & Reid, N. (1981). *Chemistry about us*. London: Heinemann Educational Books.

Kalkanis, G., Hadzidaki, P., & Stavrou, D. (2003). An instructional model for a radical conceptual change towards quantum mechanics concepts. *Science Education, 87*, 257–280.

Kemble, E. C. (1937). *The fundamental principles of quantum mechanics* (pp. 243–244). New York: McGraw-Hill [reprinted by Dover].

Kontogeorgiou, A., Bellou, J., & Mikropoulos, T. A. (2007). Visualizing the quantum atom. In R. Pintó & C. Digna (Eds.), *Contributions from science education research* (pp. 465–475). Dordrechet: Springer.

Kuhn, T. (1970). *The structure of scientific revolutions* (2nd ed.). Chicago: University of Chicago Press.

Lewis, G. N. (1923). *Valence and the structure of atoms and molecules*. New York: The Chemical Catalog Company.

Marton, F. (1981). Phenomenography – Describing conceptions of the world around us. *Instructional Science, 10*, 177–200.

Matthews, M. R. (2007). Models in science and in science education. *Science Education, 16*, 647–652.

McKelvey, D. R. (1983). Relativistic effects on chemical properties. *Journal of Chemical Education, 60*, 112–116.

Mortimer, E. F., & Scott, P. (2003). *Meaning making in secondary science classroom*. Maidenhead: Open University Press.

Nakhleh, M. B. (1993). Are our students conceptual thinkers or algorithmic problem solvers? *Journal of Chemical Education, 70*, 52–55.

Nakiboğlu, C. (2003). Instructional misconceptions of Turkish prospective chemistry teachers about atomic orbitals and hybridization. *Chemistry Education Research and Practice, 4*, 171–188.

Nakiboğlu, C. (2008). Using word associations for assessing non major science students' knowledge structure before and after general chemistry instruction: The case of atomic structure. *Chemistry Education Research and Practice, 9*, 309–322.

Nersessian, N. (1992). How do scientists think? Capturing the dynamics of conceptual change in science. In R. N. Giere (Ed.), *Minnesota studies in the philosophy of science* (pp. 3–45). Minneapolis: University of Minnesota Press.

Niaz, M., & Femández, R. (2008). Understanding quantum numbers in general chemistry textbooks. *International Journal of Science Education, 30*, 869–901.

Nicoll, G. (2001). A report of undergraduates' bonding misconceptions. *International Journal of Science Education, 23*, 707–730.

Nicoll, G., Francisco, J., & Nakhleh, M. (2001). A three-tier system for assessing concept map links: A methodological study. *International Journal of Science Education, 8*, 863–875.

Novak, J. D. (2002). Meaningful learning: The essential factor for conceptual change in limited or inappropriate propositional hierarchies leading to empowerment of learners. *Science Education, 86*, 548–571.

Ogborn, J., Kress, G., Martins, I., & McGillycuddy, K. (1996). *Explaining science in the classroom*. Milton Keynes: Open University Press.

Olsen, R. V. (2001). *A study of Norwegian upper secondary physics specialists' understanding of quantum physics*. Paper presented at the 3rd ESERA Conference, Thessaloniki, Greece.

Papaphotis, G., & Tsaparlis, G. (2008a). Conceptual versus algorithmic learning in high school chemistry: The case of basic quantum chemical concepts, part 1. Statistical analysis of a quantitative study. *Chemistry Education Research and Practice, 8*, 323–331.

Papaphotis, G., & Tsaparlis, G. (2008b). Conceptual versus algorithmic learning in high school chemistry: The case of basic quantum chemical concepts, part 2. Students' common errors, misconceptions, and difficulties in understanding. *Chemistry Education Research and Practice, 8*, 332–340.

Park, E. J., & Light, G. (2009). Identifying atomic structure as a threshold concept: Student mental models and troublesomeness. *International Journal of Science Education, 31*, 233–258.

Pauling, L. (1938). *The nature of the chemical bond* (1st ed.). Ithaca: Cornell University Press.

Pauling, L., & Wilson, E. B., Jr. (1935). *Introduction to quantum mechanics with applications to chemistry*. New York: McGraw-Hill.

Petri, J., & Niedderer, H. (1998). A learning pathway in high-school level quantum atomic physics. *International Journal of Science Education, 20*, 1075–1088.

Pople, J. A. (1999). Nobel lecture: Quantum chemical models. *Reviews of Modern Physics, 71*, 1267–1274.

Sánchez Gómez, P. J., & Martín, F. (2003). Quantum versus 'classical' chemistry in university chemistry education: A case study of the role of history in thinking the curriculum. *Chemistry Education Research and Practice, 4*, 131–148.

Scerri, E. (2001). The new philosophy of chemistry and its relevance to chemical education. *Chemistry Education Research and Practice, 2*, 165–170.

Scott, P. H., Mortimer, E. F., & Aguiar, O. G. (2006). The tension between authoritative and dialogic discourse: A fundamental characteristic of meaning making interactions in high school science lessons. *Science Education, 90*, 605–631.

Shiland, T. W. (1997). Quantum mechanics and conceptual change in high school chemistry texts. *Journal of Research in Science Teaching, 34*, 535–545.

Simons, J. (1991). There are no such things as orbitals – Act two. *Journal of Chemical Education, 68*, 131–132.

Stamovlasis, D., Tsaparlis, G., Kamilatos, C., Papaoikonomou, D., & Zarotiadou, E. (2004). Conceptual understanding versus algorithmic problem solving: A principal component analysis of a national examination. *The Chemical Educator, 9*, 398–405.

Stamovlasis, D., Tsaparlis, G., Kamilatos, C., Papaoikonomou, D., & Zarotiadou, E. (2005). Conceptual understanding versus algorithmic problem solving: Further evidence from a national chemistry examination. *Chemistry Education Research and Practice, 6*, 104–118.

Stamovlasis, D., Dimos, A., & Tsaparlis, G. (2006). A study of group interaction processes on learning lower secondary physics. *Journal of Research in Science Teaching, 43*, 556–576.

Stefani, C., & Tsaparlis, G. (2009). Students' levels of explanations, models, and misconceptions in basic quantum chemistry: A phenomenographic study. *Journal of Research in Science Teaching, 46*, 520–536.

Stofflett, R. T., & Stoddart, T. (1994). The ability to understand and use conceptual change pedagogy as a function of prior content learning experiences. *Journal of Research in Science Teaching, 31*, 31–51.

Taber, K. S. (2001). Building the structural concepts of chemistry: Some considerations from educational research. *Chemistry Education Research and Practice, 2*, 123–158.

Taber, K. S. (2002a). Conceptualizing quanta – Illuminating the ground state of student understanding of atomic orbitals. *Chemistry Education Research and Practice, 3*, 145–158.

Taber, K. S. (2002b). Compounding quanta – Probing the frontiers of student understanding of molecular orbitals. *Chemistry Education Research and Practice, 3*, 159–173.

Taber, K. S. (2005). Learning quanta: Barriers to stimulating transitions in student understanding of orbital ideas. *Science Education, 89*, 94–116.

Taber, K. S., & Watts, M. (2000). Learners' explanations for chemical phenomena. *Chemistry Education Research and Practice, 1*, 329–353.

Tsaparlis, G. (1993). *Orbitales atomiques et conceptions pertinentes: Idées fausses des étudiants de chimie*. In Actes/Proceedings 1st ECRICE: Le Bulletin du CIFEC, Numero: Hors Serie (Vol. 2, pp. 212–216). Montpellier, France: Centre International Francophone pour l' Education en Chimie.

Tsaparlis, G. (1997). Atomic orbitals, molecular orbitals and related concepts: Misconceptions and difficulties in understanding among chemistry students. *Research in Science Education, 27*, 271–287.

Tsaparlis, G. (2001). Towards a meaningful introduction to the Schrödinger equation through historical and heuristic approaches. *Chemistry Education Research and Practice, 2*, 203–213.

Tsaparlis, G. (2008). Teaching and learning physical chemistry – Review of educational research. In M. D. Ellison & T. A. Schoolcraft (Eds.), *Advances in teaching physical chemistry* (pp. 75–112). Washington, DC: American Chemical Society/Oxford University Press.

Tsaparlis, G., & Papaphotis, G. (2002). Quantum-chemical concepts: Are they suitable for secondary students? *Chemistry Education Research and Practice, 3*, 129–144.

Tsaparlis, G., & Papaphotis, G. (2009). High-school students' conceptual difficulties and attempts at conceptual change: The case of basic quantum chemical concepts. *International Journal of Science Education, 31*, 895–930.

Van Driel, J. H., & Verlop, N. (1999). Teachers' knowledge of models. *International Journal of Science Education, 21*, 1141–1153.

Vosniadou, S., Ioannidis, C., Dimitrakopoulou, A., & Papademetriou, E. (2001). Designing learning environments to promote conceptual change in science. *Learning and Instruction, 11*, 381–419.

Vygotsky, L. (1962). *Thought and language*. Cambridge, MA: MIT Press.

Wikipedia. Naïve realism. http://en.wikipedia.org/wiki/Na%C3%AFve_realism. Accessed 20 April 2013.

Ziellinski, T. J. (2005). Introducing JCE LivTexts: Physical chemistry. *Journal of Chemical Education, 82*, 1880.

Zoller, U. (1990). Students' misunderstandings and misconceptions in college freshman chemistry (general and organic). *Journal of Research in Science Teaching, 27*, 1053–1065.

Zoller, U. (1993). Lecture and learning: Are they compatible? Maybe for LOCS; unlikely for HOCS. *Journal of Chemical Education, 70*, 195–197.

Zoller, U., Lubezky, A., Nakhleh, M. B., Tessier, B., & Dori, J. (1995). Success on algorithmic and LOCS vs. conceptual chemistry exam questions. *Journal of Chemical Education, 72*, 987–989.

Zoller, U., & Tsaparlis, G. (1997). Higher- and lower-order cognitive skills: The case of chemistry. *Research in Science Education, 27*, 117–130.

Part VI
History and Philosophy of Science

Investigating the Historical Development of the Concept of Matter: Controversies About/In Ancient Atomism

Constantine D. Skordoulis and Vangelis Koutalis

Introduction

It has been argued that the role of the history of atomism should be a basic component in all science curricula. Recent discussions on atomism and its history in school textbooks and curricula can be found in Rodriguez and Niaz (2002, 2004), Justi and Gilbert (2000), and Izquerdo-Aymerich and Adúriz-Bravo (2009). However, science educators should consider that the history of atomism and its position in the history of science are still a matter of debate.

Recently, Alan Chalmers[1] (2009) published a book in which he surveys the history of atomism from Democritus to the twentieth century, examining the varying contexts in which science has been practised.

In this book, Chalmers sees modern atomic theory as the recent legacy of experimental science as it emerged in the seventh century rather than a tradition of speculative philosophy dating back to Democritus and extending to seventeenth-century mechanical philosophy and beyond.

Chalmers believes that a distinction between philosophical metaphysics and experimental philosophy emerged, and was made explicit, in the seventeenth century. His book intends to demonstrate that we learn much about science by recognizing

[1] Alan Chalmers is one of the key figures in the international community of the philosophy of science. His book *What is this thing called Science* (St Lucia, Queensland: University of Queensland Press, 1976) is considered as the standard textbook for every student entering the field. The book has been translated into French, German, Spanish, Italian, Portuguese, Dutch, Greek, Norwegian, Danish, Polish, Estonian, Latvian, Japanese, Chinese, Korean, Indonesian, Turkish and Iranian.

C.D. Skordoulis (✉)
Department of Primary Education, University of Athens, Athens, Greece
e-mail: kostas4skordoulis@gmail.com

V. Koutalis
Department of Chemistry, University of Ioannina, Ioannina, Greece

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_22,

the way in which, by the beginning of the twentieth century, a general atomic theory of matter that was experimentally supported had come about in a way that owed little to the philosophical versions of atomism that had origins in Ancient Greece.

Towards the end of his book, Chalmers writes:

> The atoms invoked by Ancient Greeks such as Democritus and Epicurus and by seventeenth-century mechanical philosophers such as Gassendi and Boyle were construed as the ultimate and unchanging components of material reality. Twentieth-century atoms are nothing like those envisaged in these philosophical traditions and they and their properties were discovered by experiment rather than philosophical analysis. The modern atom has an internal structure, most importantly an electron structure. Electrons have a charge as well as a mass, electrons have a half-integral spin, a quantum mechanical notion having no classical correlate. Such properties are far from anything envisaged by Democritus and Boyle and cannot be reconciled with the notions of reality and intelligibility that informed their theories. (Chalmers 2009, p. 262)

Chalmer's key theme was stated 11 years earlier in an article titled 'Retracing the Ancient Steps to Atomic Theory'. This article opens with the claim that

> In an article published recently in this journal, Sotirios A. Sakkopoulos and Evagelos G. Vitoratos [vol. 5 no. 3, 1996] observe that teachers of today can with benefit to their students, retrace the ancient steps to atomic theory. I agree with them, but for reasons that are diametrically opposed to theirs. Sakkopoulos and Vitoratos apparently see a study of the history of atomism to be valuable to the extent that arguments introduced in atomic theories of the past have their analogues in modern atomic theory. Consequently, an appreciation of the historical arguments is seen as illuminating contemporary theory. By contrast, I claim that a study of past atomic theory can serve to illustrate some features of contemporary science because of the significant differences between the two. Versions of atomism prior to Dalton, were philosophical rather than scientific theories, and appreciating the difference between the two tells us something important about science. (Chalmers 1998, p. 69)

More of Chalmer's argument is presented in the conclusion of the article where he writes that

> Whilst it is true to observe that the modern list of properties [of the atom] is different from, and lengthier than, that of Democritus, there is more to it than that. The modern properties are scientific properties, attributed to particles for reasons that stem from within science itself. They were not, and could not have been, anticipated by any philosophy. The properties ascribed to atoms by the philosophers, from Democritus to Boyle, had their origins in common sense and were attributed to atoms for philosophical reasons prior to and independent of scientific research. (Chalmers 1998, p. 82)

It is obvious that for Chalmers, atomism as a philosophical theory of the composition of bodies, an ontological position, had little, if anything, to do with the development of modern scientific practice.

Chalmers' positions have been critically discussed by M. R. Matthews (2009) in a book review published *in the monthly Newsletter of the IHPST Group*. Matthews criticizes Chalmers on two themes that are central to science education: first, the role of atomism in the history of science, which is basic in all science curricula and, second, the issue of realism and instrumentalism in philosophy of science, insisting that the overarching question that Chalmers' book deals with is the proper understanding of the role of philosophy and metaphysics in the history and current practice of science.

Matthews recognizes that for Chalmers, theory-guided experimentation is the *differentia* of modern scientific atomism, and this is why there is a break between the tradition of philosophical atomism and the origin of scientific, experimental atomism. However, he defends the importance of ancient Greek atomism for modern scientific atomism on the basis of the continuity of the materialist programme initiated by the Greek atomists Democritus and Epicurus, who inspired the Roman poet Lucretius to write the poem *De Rerum Natura – The Nature of Things* in the middle of the first century B.C.E. The poem was the only full expression of classical materialism to survive the ancient world. Then, for a millennium and a half, Greco-Roman materialism disappeared from European civilization, driven underground by Christianity or more precisely by the Christian adaptation of the Aristotelian hylomorphic anti-atomism, tentatively resurfacing in seventeenth-century England and France in the writings of Francis Bacon and Pierre Gassendi.[2]

In the light of this debate, in this chapter we will examine more closely the philosophical import of the early atomism, by relating Leucippus' and Democritus' theory to the chief tenets of the Eleatic school of thought. We will also try to ascertain what ramifications did the Eleatic conception of being have for the philosophical projects of Plato and Aristotle. This flashback to the ancient Greek philosophy can help us better evaluate the particularity of early atomism, and its potential relevance to present-day science education.

Sure enough, the modern reader may find it hard to see how those distant philosophical speculations could be relevant to the instruction in scientific understanding, unless they would somehow be reckoned as forming the introductory part of historical narratives leading to our present. It is usual to treat the past both as the background which explains our own history *and* as the prelude to an unavoidable and necessary course, as the part preceding and preparing for the principal matter: the achievements of our culture, which are thus, in one way or another, vindicated at the outset. The key point raised by Chalmers here is that science educators should be weaned away from that habit. Natural philosophy is not simply the immature form of modern natural science. Leucippus should not be portrayed as the progenitor of Dalton. And it is perhaps still more significant the fact that the same stricture holds also for Leibniz, Newton or Boyle.

Leibniz' structural theory of matter, for example, does indeed necessitate an explicit and direct conjunction of physics and metaphysics and an incessant regression from the knowledge of facts to the knowledge of general laws and universal principles, rendering possible the representation of natural phenomena as determined by unobservable causes underlying them, which are accessible to reason (see Hassing 2003). The spatial world of bodies is conceived as a set of phenomenal

[2]Interestingly enough though, Chalmers does draw attention to the atomistic element of Aristotelianism, namely, its belief in a natural minima or corpuscles. Aristotle held that matter could be divided downwards into smaller and smaller pieces till a physical limit was reached. But he is careful to insist that these minima were not Democritean atoms and they did not require a void; they were just minimum parts of the whole and had properties of the whole.

relations among substances the reality of which is assigned to an ultimate ontological order, of metaphysical points or monads. Physics virtually rests upon metaphysics: 'although all the particular phenomena of [corporeal] nature can be explained mathematically or mechanically by those who understand them, it nevertheless appears more and more that the general principles of corporeal mechanical nature itself are metaphysical rather than geometrical, belonging to forms or indivisible natures functioning as causes of the <matter or extension> rather than to corporeal or extended mass' (Leibniz 1988, p. 61).

Not less reminiscent of the linking of physics with metaphysics is Newton's appeal to the 'analogy of nature', through which he justified his assumption that the imperceptible indivisible particles possess the same qualities as the perceptible large-scale bodies: extension, hardness, impenetrability, mobility and inertia. Maxwell, many years later, dismissed the dogma of the impenetrability of matter, the opinion, shared by both Leibniz and Newton, 'that two bodies cannot co-exist in the same place', as 'vulgar'. 'This opinion is deduced from our experience of the behavior of bodies of sensible size, but we have no experimental evidence that two atoms may not sometimes coincide' (Maxwell 1890, p. 448). Why should the microcosm be analogous to the macrocosm? Molecular forces, on the contrary, seem to act differently from the forces acting within the domain of sensible experience. But this does not imply that the knowledge of molecular dynamics involves any new kind of philosophical speculation on that unknown substratum of bodies hitherto called 'matter'. In the science of dynamics, 'matter' means no more than 'mass', a certain quantitative value which can be specified for each particular body and each particular portion of a body.[3] The view that the concept of matter is redundant, since it designates a metaphysical 'substance' or substratum, was later championed by Mach, and upheld also by some of the founding fathers of quantum mechanics, such as Bohr, Heisenberg and Pauli.

Yet, as Karl Popper once remarked 'the wonderful theories of these great physicists are the result of attempts to understand the structure of the physical world, and to criticize the outcome of these attempts'. The metaphysical speculations on the structure of matter, discussed and criticized from the classical antiquity to the early modernity, were inspired by the same wish to understand the world and motivated by the same hope for a better life:

> Thus their own physical theories may well be contrasted with what these physicists, and other positivists, try to tell us today: that we cannot, in principle, hope ever to understand anything about the structure of matter: that the theory of matter must forever remain the private affair of the expert, the specialist – a mystery shrouded in technicalities, in mathematical techniques, and in 'semantics': that science is nothing but an instrument, void of any philosophical or theoretical interest, and only of 'technological' or 'pragmatic' or 'operational' significance. I do not believe a word of this post-rationalist doctrine. (Popper 1992, pp. 20–21)

Neither do we. Instruction in science should denote something more than building effective technical skills. Doing science cannot be reduced into the ability of suitably handling a set of formalisms. In the very region of post-classical, highly formalized

[3] Our succinct account of Maxwell's theses on the problem of impenetrability and the concept of matter is based on the analysis of Harman (1988, pp. 175–208).

physics, the persistent problem of interpreting quantum mechanics has already stimulated interest in some, seemingly impertinent (in natural science proper), metaphysical and ontological questions, bringing Kant's, Hume's, Aristotle's, Plato's, or even Parmenides' and Democritus' conceptions of reality and of the knowability of reality, back into play (see Aerts 1981; Piron 1983; Bohm and Hiley 1993; Verelst and Coecke 1999; de Ronde and Christiaens 2010). Maxwell himself, in his inaugural address at Marischal College, Aberdeen, in 1856, told his audience that 'those who have raised objections to the engrossing pursuit of physical science have done so on the ground of the supposed effects of exact science in making the mind unfitted to receive truths which it cannot comprehend', but quite the opposite is the case: 'it is the peculiar function of physical science to lead us to the confines of the incomprehensible' (Maxwell 1990, p. 427). It is for this reason that we think it is worth trying to carry further Chalmers' point: not only to stress the difference between the early and the modern atomisms but also to explore that which is different, and incomprehensible as such.

Responding to the Eleatic Challenge

The early atomists developed their theory responding to problems posed by the Eleatic school, such as Parmenides' distinction between truth and appearance, Zeno's paradoxes concerning the divisibility, and Melissus' denial of the reality of the void (Curd 2004, p. 215).

Melissus, in a fragment preserved by Simplicius in his commentary on Aristotle's *Physics*, had declared that what-is can only be full:

> For what is empty is nothing, and of course what is nothing cannot be. Nor does it move. For it cannot give way anywhere, but is full. For if it were empty, it would give way into the empty part. But since it is not empty it has nowhere to give way …
>
> And we must make this the criterion of full and not full: if something yields or is penetrated, it is not full. But if it neither yields nor is penetrated, it is full.
>
> Hence it is necessary that it is full if it is not empty. Hence if it is full it does not move.[4]

Leucippus, the alleged founder of atomism,[5] according to the reconstruction of his basic theoretical tenets performed by Aristotle, converted Melissus' denial into an

[4] '(7) οὐδὲ κενεόν ἐστιν οὐδέν· τὸ γὰρ κενεὸν οὐδέν ἐστιν· οὐκ ἂν οὖν εἴη τό γε μηδέν. οὐδὲ κινεῖται· ὑποχωρῆσαι γὰρ οὐκ ἔχει οὐδαμῆι, ἀλλὰ πλέων ἐστιν. εἰ μὲν γὰρ κενεόν ἦν, ὑπεχώρει ἂν εἰς τὶ κενόν· κενοῦ δὲ μὴ ἐόντος οὐκ ἔχει ὅκηι ὑποχωρήσει … (9) κρίσιν δὲ ταύτην χρὴ ποιήσασθαι τοῦ πλέω καὶ τοῦ μὴ πλέω· εἰ μὲν οὖν χωρεῖ τι ἢ εἰσδέχεται, οὐ πλέων· εἰ δὲ μήτε χωρεῖ μήτε εἰσδέχεται, πλέων. (10) ἀνάγκη τοίνυν πλέων εἶναι, εἰ κενὸν μὴ ἔστιν. εἰ τοίνυν πλέων ἐστίν, οὐ κινεῖται', Fr. 30B7, Diels and Kranz (1960, I, pp. 272–273). We have used the English translation given by Richard McKirahan (2010, p. 295).

[5] In fact, we know nothing of Leucippus' life. His successor Democritus overshadowed him in such a degree that Epicurus later denied that any philosopher with the name Leucippus ever existed. The extremely scarce hints we can find in ancient sources concerning his writings may only lead us to the assumption that he may have composed two works, the one entitled *Great World-System* and the other *On Mind* (there is also the possibility that the latter was just a portion of the former); see Taylor (1999, p. 157).

affirmation of the void's possibility. His theory was intended to fulfil the need for an explanation of natural phenomena that 'would grant to perception what is generally agreed, and would not do away with coming to be or passing away or motion or the plurality of things'. Phenomena should be explained as phenomena: their reality should not be altogether discarded as illusionary. So, he agreed both with the Eleatic definition of the void as 'what is not' and with the statement that motion is impossible, unless there is void. But he made the choice not to equate what-is-not with non-being. What-is-not, i.e. the void, exists no less than what-is: 'both are alike causes of the things that come to be'. If motion requires the existence of void, then there must be a place in reality for the void, since in reality, as we perceive it, motion actually takes place. Indeed, what-is, in the strict sense of the term, is completely full. What-is, that other section of reality which is complementary to what-is-not, is a 'total plenum'. This plenum, however, is not merely one thing. What-is consists of 'infinitely many things, invisible because of their small size', which 'move in the void'. These, infinitely many, things that constitute what there is, which, for Melissus, ought to be 'one and all alike',[6] are essentially susceptible to action. 'They act and are acted upon as they happen to come into contact, for in that way they are not one, and they generate by being combined and entangled together'. Coming-to-be and passing-away are produced, respectively, by their combinations and their separations. The multiplicity of attributes and substances that we encounter in our reality can be explained by positing an infinity of principles, 'as matter of the things that there are', entities 'of the same kind', differing from each other in nothing but their shape, position, and arrangement, which move through the void, traversing what-is-not, towards one another, 'for it is natural for like to be affected by like', while each of the shapes can be reorganized 'into a different complex and so make another state'.[7] Should we take Aristotle's description to the letter, Leucippus asserting 'what is granted to perception' came up with the notion of the 'atom', of a principle evading perception and nonetheless underlying phenomenal world, being the compact, indestructible core of reality, responsible for whatever we perceive as real.

Another celebrated Eleatic thinker, Zeno, had demonstrated that in reality there can be no motion, or, at least, that the way we usually form the impression of motion is logically inconsistent; it may easily be rebutted by evidence brought forward by thinking, by the faculty of reasoning. To have the sense of moving is to have the sense of traversing a finite distance in space. But that which is moving has first to reach the midpoint before reaching the end of the distance to be covered, and the number of midpoints is shown to be infinite. Since space can be infinitely divided by thought, motion in space, as sensed by our bodily organs, is merely an illusion.[8]

[6] 'οὕτως οὖν ἀίδιόν ἐστι καὶ ἄπειρον καὶ ἓν καὶ ὅμοιον πᾶν', Fr. 30B7, Diels and Kranz (1960, I, p. 270). Translation by McKirahan (2010, p. 294).

[7] The quotations in this paragraph are from two fragments indicative of Leucippus' theory, preserved by Aristotle (*De Generatione et Corruptione* A.8 325[a], 25–35, Fr 67A7, Diels and Kranz 1960, II, pp. 72–73) and Simplicius (*Physica* 28.4-26 = Fr 67A8, 68A38, Diels and Kranz 1960, II, pp. 73–74, 94). We have used the translation given by Taylor (1999, pp. 71–74). Cf. also the translation of McKirahan (2010, pp. 305–306).

[8] For this argument, see McKirahan (2010, pp. 181–184).

In another instance, reported by Simplicius, Zeno is said to have proven that what-is can be thought of as just and only one, partless and indivisible, thing. Let's suppose that we are presented with a body known to be divisible, and of a measurable, finite size. If we start cutting it into pieces until the division is complete, then either we reach some parts that remained intact, and are thus uncuttable, or we reach a point where the thing we have just divided disappears. The logical consequence to draw is either that the body the divisibility of which we tested was made up of nothing, since nothing remained after the division, or that it was made up of infinitely small particles, which must be infinite in their number too, and this means that if we put those pieces back together, the aggregate ensued would be a body of infinite size.[9] In either case, our knowledge of its divisibility is illusionary.

We do not intend to revisit, here, the historiographical and philosophical debate over Zeno's paradoxes. We need only recall that according to the available evidence, the surviving arguments of Zeno, both those directed against motion and those directed against plurality were in his own time treated more as metaphysical or ontological arguments, addressing conceptual problems, than as mathematical riddles (see Owen 1957–1958; Vlastos 1967; Hasper 2006a). The impasse towards which he pointed was a conceptual knot faced by any enterprise to speak of what-is by uncritically endorsing the intuitions of common sense: when thought *reflects* actuality, when it mirrors the world, as the latter is being monitored by the senses, then it inevitably yields pairs of contradictory attributes, but if contradictory predicates are predicated of one and the same object, that object cannot *be*.[10] Leucippus and his associate Democritus, moulding a theory of indivisible magnitudes, in which reality is represented as an infinite space – the void – where an infinite number of atoms act and are acted upon, succeeded in showing that the impasse could be unblocked[11]: thinking, not sensing, might quite well explain the alterations testified by the senses without negating them as such, as alterations. Space is infinitely divisible, but this holds true only in the case of the void, only for what-is-not. Atoms, the matter of what-is, are not divisible. They are not so by definition. The knowledge of atoms and void is knowledge acquired through conceptual work: we don't see them; we know what they must be and what they can do after we have situated them within a conceptual constellation. Thought can avoid contradictory predication when it *reflects upon* reality, when it actively reconstructs reality, correcting or even defying common sense, instead of functioning as a faithful mirror. A distinction should be established between what is real and what is actual, what we can think of as being, and what we can perceive as tangibly being there, without however negating the experience of the

[9] Here, we have closely followed the description of Zeno's paradox given by Curd (2004, pp. 173–174).

[10] In this sense, Zeno could be credited with the invention of the principle of contradiction, as an ontological principle, though not as a logical axiom, as it is presently regarded to be. See Hoffmann (1964) and Prauss (1966).

[11] David Furley revisiting Aristotle's criticism has pointed out that Leucippus and Democritus considered atoms to be both physically and theoretically divisible, providing thus a response to Zeno's paradoxes (1967, pp. 79–103).

actual itself: 'tangibility ceases to be the criterion of existence, although it remains the touchstone of reality' (Pyle 1995, p. 46). This is why Democritus could declare that atoms and void are 'in reality', whereas sweet, bitter, hot, cold, and colour, all those sensations, are 'by convention'[12]: the latter pertain to subjective feeling, the former to objective being. And due to Parmenides, the founder of the Eleatic school, Democritus and Leucippus already knew that what thought intends to is that which is out there to be known as real.

Parmenides' Bare 'Is'

Appealing to audiences familiar with the epic poetry of Homer or Hesiod, Parmenides had appropriated and transformed epic motifs, themes, and imageries, as well as shamanist thought patterns, in order to develop and to present, by reworking that inherited discursive material, a set of philosophical arguments,[13] involving prominently the problem of how true knowledge of what there is can be possible in terms of a quest or journey, undertaken by a mortal being confined within the bounds set by fate. No matter how much we may try to alleviate the difficulty of operating at such a cultural distance, by insisting that we should treat Parmenides' didactic poem in nearly the same manner as we are used to decode a piece of prose (Diels 1897, p. 47), or even that under its metric form we should recognize 'the earliest philosophic text which is preserved with sufficient completeness and continuity to permit us to follow a sustained line of argument' (Kahn 1969, p. 700), any historical reconstruction of Parmenides' philosophy is doomed to raise far more questions than it answers.

We cannot be sure even of what could we specify to be the logical subject of his two fundamental, and complementary to each other, statements: 'ἡ μὲν ὅπως ἔστιν τε καὶ ὡς οὐκ ἔστι μὴ εἶναι … ἡ δ' ὡς οὐκ ἔστιν τε καὶ ὡς χρεών ἐστι μὴ εἶναι'

[12] 'νόμῳ γλυκὺ καὶ νόμῳ πικρόν, νόμῳ θερμόν, νόμῳ ψυχρόν, νόμῳ χροιή· ἐτεῇ δὲ ἄτομα καὶ κενόν', Fr 68B9, Diels and Kranz (1960, II, p. 139). Translation by Taylor (1999, p. 9).

[13] As for the appropriation of epic and shamanist poetry by Parmenides, see the analysis of Mourelatos (2008, pp. 1–46). Eric Havelock, several years before Mourelatos published his book, had also argued in favour of a similar reading, matching certain images present in Parmenides' poem against devices used by the author of the *Iliad* and the *Odyssey* (Havelock 1958). This interpretation remains controversial. Leonardo Tarán rejects the idea that rooting Parmenides in the epic tradition may cast new light upon his thought: 'that tradition had long been dead as a creative force by the time Parmenides wrote, and it is hardly credible that he, born and raised in Southern Italy, could have conceived his philosophy in the very language and meter of the epic'. Moreover, 'despite the linguistics parallels between Parmenides and Homer, no motif of "The-Journey" is common to the two' (Tarán 1977, pp. 653–658). Notwithstanding the possible inaccuracies in Mourelatos' and Havelock's interpretation, we think that it fosters an awareness of the distance separating metaphysics, as we, from our present standpoint, understand it, and the inquiry into what-is situated within a quite different, ancient mentality. See also the extensive analysis of Wilkinson on Homer, Parmenides, and the distinction between mythos and logos, 2009, pp. 10–39, 69–79.

(Fr. 28B2.3-5, Diels and Kranz 1960, I, p. 231). Given the context of these words in the fragment, we may safely assert that the first statement refers to one of the alternative routes of inquiry offered to mortals, the way of reliable conviction or persuasion,[14] the proper path to knowledge, and the one promising to furnish truth. The second refers to another conceivable way, a trail which no one can actually follow, that of ignorance, of the impossibility of inquiring into anything and knowing anything. And after Karl Reinhardt's work (1916, pp. 32–51), we also know that in Parmenides' text, there is an additional, third course, where 'what-is' is represented both as being and as not being.[15] This is the beaten path followed by mortals, their attention being constantly riveted on the world as it deceptively appears to them, from which 'Kouros', the traveller and first-person narrator of the poem, is warned by the Goddess, who guides him through his ecstatic journey into the Beyond, to stay away. What-is-not (μὴ ἐὸν) cannot be known, thought, or spoken of (Fr 28B2.7-8, Fr 28B8.8-9, Diels and Kranz 1960, I, pp. 231, 236), and what appears to be is not what-is. But precisely what is that which Parmenides avers that it is? Simon Kastner, presenting in 1835 the first complete edition of Parmenides fragments, translated in Latin, rather literally, the two sentences, as 'altera, quod est neque potest non esse … altera, quod non est et quod necesse est non esse'[16] (1835, p. 33). The issue of whether there is a suppressed logical subject, and what would we assume it to be, remained in suspense and, in fact, still so remains.[17]

Some scholars interpret these sentences as ontological assertions, while others translate them in a manner that highlights more their metaphysical and epistemological import or even their metalinguistic function. So, following the first, and more traditional, line of interpretation, Parmenides' bare 'is' can be regarded as an existential verb supplied with a noun, or a noun phrase, as its subject, denoting the entity whose existence is being asserted: here, it is averred that something exists. And we may determine what is declared to exist by supposing that our missing subject is 'reality', 'all that exists', and 'being'[18] or, in a more recent and elaborate version of that interpretation, 'what is there for speaking and thinking of' (Gallop 1984, pp. 8, 61), 'whatever we inquire into' (Barnes 1982, p. 128), and 'what can be talked or thought about' (Owen 1960, p. 95). Another choice is to assume that the verb 'to be' has no subject here at all, either because it is impersonal (Fränkel 1946, p. 169; Tarán 1977, note 30, p. 662) or because it is placed in propositional constructions which

[14]'Πειθοῦς ἐστι κέλευθος (Ἀληθείηι γὰρ ὀπηδεῖ)', Fr. 28B2.4, Diels and Kranz (1960, I, p. 231).

[15]Tarán (1965, pp. 59–72), Cordero (1979), and Nehamas (1999, pp. 125–132) still disagree with that view, which has achieved canonical status among contemporary scholars. They think that there is no third path or that the alleged third path falls into the second: the way of not being and that in which being and not being are confused are virtually the same.

[16]We could literally translate Karsten's version in English as 'the one [way], that is and cannot not be … the other, that is not and necessarily is not being'.

[17]For a detailed presentation of the debate from the 1930s to the 2000s, see Cordero (2004, pp. 46–54).

[18]For an account of this interpretation and extensive bibliography, see Marcinkowska-Rosól (2010, pp. 45–48).

serve as premises of a syllogism, as the preliminary steps of an argument intended to progress and to let meanings gradually unfold. At the end of the argumentation process, a key concept may come out, as the centre around which all else revolves, and that concept can be plausibly designated as that which 'is'. Once more, there are a few potential candidates to consider for filling this post: 'being' (Mansfeld 1964, p. 90; Tarán 1965, pp. 33, 37; Coxon 1986, pp. 20, 174–175), any subject of enquiry, whatever it may be (Kirk et al. 1983, p. 245), or the verb 'to be' itself, elevated to the status of a concept pointing to the very fact of being (Cordero 2004, pp. 51–52). A third alternative is to settle on a 'veridical' reading, translating the Greek verb 'εἶναι' as 'to be so', 'to be the case', or 'to be true', rather than 'to exist'. Thus, Parmenides' statements could be decoded as expounding a doctrine concerned less with the reality itself than with how could we gain knowledge of what-is and how could we properly think and speak of what is the case (Kahn 1966, 1969). A similar emphasis on the strictly logical aspects of Parmenides' statements is to be found in yet another, fourth line of interpretation, according to which the ἔστιν, in the fragment 28B2, is just an element in an affirmative statement, a copula, performing primarily a logical function. The controversial lines 3 and 5 of the fragment could be, therefore, translated as follows: 'the one [way] <which says> that is and that it is not possible not to be … the other [way] <which says> that is not and that it is necessary not to be'.[19] The logical notion of the verb 'to be' can be further stressed by reconstructing Parmenides' statements as answers to the question 'What one may say?', as metalinguistic: 'Negative judgments are impossible, for they refer to nothing. Positive judgments are possible, but only insofar as they say no more than "is"'. 'To be' is interpreted as fundamentally predicative, as a copula 'but with both the subject and the predicate-complement left blank' (Mourelatos 2008, pp. 52, 55). In terms of its grammatical function, the bare 'is' plays the common role of a copula but logically may function as the 'is' of identity, making thought capable of connecting things and thus establishing identities. 'To be' garners the meaning of 'to be what it is to be'. Parmenides managed to discard the possibility of change and plurality by constructing the following logical formula: 'real things, things that are *F* in the strong sense of being what it is to be *F*, cannot change', because 'to be what it is to be *F*, to be the nature of *F*, is to be *F* in every way and at all times' (Nehamas 1999, pp. 133–134).

Parmenides pondered over the possibility of being, over the possibility of knowing what being is, and over the possibility of the language conveying the knowledge of being: the debate on the possible logical subject of 'is' reveals the multiplicity of problems that are inherent in any conceptualization of what-is. Perhaps, the most important outcome of Parmenides' effort to conceptualize being is the awareness of the fact that crafting a concept which is meant to correspond to something real is always an interesting problem leading to more, and even more interesting, problems. How could we know something we don't know? And how could we know that we have actually received what we did not hitherto have, that we have come now to

[19] This could be an English version of Guido Calogero's translation: "l' una <che dice> che è e che non è possibile che non sia … l'altra, <che dice> che non è e che è necessario che non sia" (Calogero 1977, p. 19).

know what we knew that we did not know before? In this regard, we may assent to Karl Popper's claim that Parmenides 'found himself speaking about the unspeakable' (1998, p. 148). And what's more, he found himself opening up the horizon for thinking what he thought it was unthinkable: differentiation and change in reality. While his central argument, whether seen as chiefly ontological or as chiefly epistemological, succeeded in producing a rupture with the earlier Ionian tradition of cosmological accounts, by reducing all oppositions to the one between being and not being and by 'showing that cosmological explanations amount to the assertion of non-Being' (Tarán 1965, p. 39), nonetheless it was an argument with considerable impact on cosmology itself, representing an attempt to make headway in the direction of a radically revised, rational cosmology, both by setting standards for the rational evaluation of cosmological theories (Curd 2004, p. 125) and by posing new cosmological problems, such as that of the different modalities of being (what Plato and Aristotle later recognized as central to Parmenides' theory; Palmer 2009, p. 44) and, even more importantly, that of change (Popper 1998, p. 114).

In a way that might seem curious to our eyes, Parmenides monism opened up a horizon befitting for a variety of elaborate pluralisms to emerge. Alan Chalmers observes that Leucippus and Democritus envisaged the portions of being they called atoms to be 'themselves miniature Parmenidean worlds that are one and changeless for all the reasons that Parmenides' one, the universe as a whole, was argued to be changeless' (2006, p. 24). Curd tried to prove that the world of Parmenides was not one, in terms of number or of matter. It was one only in terms of predication: 'to be' something, in the sense of being really what that particular something essentially is: that it had to be one, to cannot not be. Leucippus and Democritus, insisting that the void, despite being defined as what-is-not, is no less real than what-is, not only echo 'the Eleatic identification of void with what-is-not, but [they are] also recalling the Eleatic understanding of what it is for something to be … Void must, on their view, qualify as a genuine entity'[20] (Curd 2004, p. 196). In the case of Parmenides, thinking was stretched beyond, and eventually turned against, its own motivation: a theory which was constructed so as to negate coming-to-be fuelled theories explaining coming-to-be, or at least ascribing to coming-to-be the status of a legitimate philosophical problem.

Speaking of the Knowledge of Reality

Aristotle waded into the problem of coming-to-be and passing-away, as Leucippus and Democritus had done before him. But the challenges he had to encounter were different from those of the early atomists. What he had to overcome was not Parmenides' theory explicitly concerning the possibility of being really something, with all of its various implications, but Plato' theory explicitly concerning the possibility of knowing what something really is, informed as the latter was by Parmenides' theory of being.[21]

[20] Curd discusses atomists' views on the reality of void in pp. 188–206. Cf. the analysis of Dayley (2006).

[21] Nehamas writes that in Plato's 'self-predication', in his frequently employed idea 'that the *F* itself is *F*, independently of any particular analysis we might give to it', we may discern the import of Parmenides' doctrine of being in 'a more fully spelled-out version' (1979, pp. 93, 98).

In some of the platonic dialogues, clear knowledge of reality is presented as coincidental with the knowledge of unchanging ideal objects, of forms. That only what is universal and lasting can be knowable, this was a conviction shared both by Plato and Aristotle. Serious differences, however, arise when we come down to specifics: Plato had described the proper process to attain that end as an operation enforcing seclusion from the sensible world, as an act of recollection, and an unconcealment[22] of the real induced by the concealment from the actual. The philosopher, the 'lover of wisdom', knowing the world, instead of being engaged in the flux of phenomena, has to become estranged from the sensory entities to be known, the moving shadows of reality that shroud and conceal reality itself, to 'look down upon the things which now we suppose to be' and to gaze up 'to that which truly is'. Only by performing such a leap into a higher and deeper, transcendental we would call it today, grade of being, the philosopher learns to speak, or rather remembers how to speak, the language of truth, which is but the 'language of Forms', 'passing from a plurality of perceptions to a unity gathered together by reasoning' (Plato 1972, p. 86, *Phaedrus* 249B-C).

This transition from the sensible actuality, the world as a cave with fleeting shadows cast upon its walls, to the intelligible reality, the world as a 'symphony of proportion', a 'Living Thing which comprehends within itself all intelligible living things' (Plato 2000a, pp. 16–17, *Timaeus* 30C, 32C), is signified as a retrieval of repressed cognitions. Anamnesis is the word denoting soul's reinstatement in the world as it is ideally depicted, as seen by the eye of the mind, which, according to Plato, is the world as it really is, an orderly fabric whose life explains the life of any of its part. Digging up the reality lying under and beyond what sense organs can capture, the soul is 'let by itself to behold objects by themselves' (Plato 1955, p. 48, *Phaedo* 66E1-2), distinct from, and superior to, sensible appearances.

Not that sensuality is totally tossed out as an index of being. Through sense perception, we become acquainted with visible things, we even can form true opinions about what sort of thing any entity we perceive is, and we can also embark upon the inquiry into the essential nature of reality by stirring up true opinions about what reality looks like.[23] The task we cannot fulfil, when we restrict ourselves to empirical investigations, is to give a rational account of what a thing essentially is, to figure out causes explaining not its actuality but its reality, establishing its relation to an intelligible object, a form, which is real, nonidentical, that is, with its particular sensible instantiations and independent of the mind which thinks of it (the beautiful explaining an actually beautiful thing, as separate both from the instances of beauty

[22] Martin Heidegger prompts us to remember that the Greek word we use to translate as 'truth' literally means 'unconcealedness'. And he does not neglect to caution against possible retrojections: 'It is therefore an idle play with 'word-forms' if we render ἀλήθεια by 'unconcealedness', as has become fashionable recently, but at the same time attribute to the word 'unconcealedness', now meant to replace the word 'truth', a significance which we have merely gleaned from the ordinary later use of the word 'truth' or which offers itself as the outcome of later thinkings' (1992, pp. 11–12).

[23] This is a point emphasized by Bedu-Addo (1983) as for the process of recollection.

and from the minds that come to understand beauty; see McCabe 1994, pp. 62–63). By being something which we can locate, as part of the world wherein we dwell, through our sensory organs, a visible thing participates in being. By not being susceptible, as such, to reasonable ascertainment, it belongs to the province of non-being as well. It is 'something' indeed, though only if we take that word literally: a shadowy presence situated between being and non-being, a perishable image uncertainly oscillating in between, "knowable' in a sense but not in the full sense; *doxa*, but not *episteme*' (de Vogel 1988, p. 53). Plato's 'lover of truth' does not feel any ascetic contempt for sensuality. But he does not feel the slightest desire for the prizes delivered inside the shadow cave of actuality to those who have been proved 'quickest at identifying the passing shapes' on the walls or those who had 'the best memory for the ones which came earlier or later or simultaneously, and who as a result are best at predicting what was going to come next' (Plato 2000b, p. 222, *The Republic*, 7, 516C-D). He does not envy the cosmologists and the physicists preceding him, and he refuses to enter into dispute with them on how to explain natural phenomena. He chooses a different ground to prosecute his intellectual enterprise, a different jurisdiction over knowledge to assert. Leucippus' atoms are images explaining the world as an image. Plato's regular geometrical solids, composed by indestructible triangles, are intelligible entities explaining an intelligible world.[24] As Aristotle once evaluated the differences between them:

> For Plato is so far from giving the same account as Leucippus that, while both of them declare that the elementary constituents are indivisible and determined of figures, (α) Leucippus holds that the indivisibles are solid, Plato that they are planes, and (β) Leucippus declares that they are determined by an infinite number of figures, Plato by a definite number. It is from these indivisibles that the coming-to-be and dissolutions result: according to Leucippus through the void and through the contact (for it is at the point of contact that each body is divisible); according to Plato, as a result of contact only, for he denies that a void exists. (Aristotle 1955, p. 243, [*On Coming-to-Be and Passing-Away*, 325^b, 25–34])

Thinking of the Reality of Change

Disqualifying sensual experience of concrete individual things as a reliable source of knowledge and installing a gradation of being which implies a sharp, permanent tension between the sensible and the intelligible, between the fluctuating entities

[24]For a detailed discussion of Plato's 'elements' and their constituent triangles, see Miller (2003, pp. 163–196). Plato persistently avoided mentioning the early atomists in his dialogues. There is a passage of Diogenes Laertius according to which Aristoxenus, in his 'Historical Notes', offers the testimony that Plato wished to burn all the writings of Democritus he could buy, but he was eventually prevented to do so by the Pythagoreans Amyclas and Clinias. Jean Bollack has argued that Plato, contrary to what we may be led to assume by reading that narration, admired Democritus and preferred not to mention his name by virtue of that name's prestige. Rein Ferwerda (1972) tried to find evidence supporting, or refuting, Bollack's theory, and after discussing possible Democritean influences on Plato, he concluded that Bollack's interpretation should be accepted.

which constitute what actually exists and the nonperishable forms which populate the ideal realm of what has been and what will once more be (after the separation of the soul from the body), Plato's account of how the obstacles barring human access to truth should be removed threatened, so Aristotle thought, to render our efforts to contemplate on, and to probe into, natural reality meaningless, to 'abolish the whole study of physics' (Aristotle 1961, I, p. 77, *Metaphysics*, A, 992^{b} 8–9). In his *Metaphysics*, Aristotle sums up his judgement of Plato's theory by noting that 'although Wisdom is concerned with the cause of visible things', this question has been ignored, since we are left with 'no account of the causes from which change arises': in the belief that we are accounting for the substance of the entities which we perceive 'we assert the existence of other substances; but as to how the latter are the substances of the former, our explanation is worthless', for 'participation', the word used by Plato to denote the imitation of the forms, 'means nothing', is not a genuine explanation and does not tell us the reason why. Philosophy, he fears, has been let to lapse into mathematics, whereas mathematics should be studied only as a means to some other end (1961, I, pp. 75–77, *Metaphysics*, A, 992^{a} 24–29, 32–33).

The last sentence in the extract above discloses, we think, one major thrust of Aristotle's criticism against Plato. To be sure, he never differed from his illustrious predecessor so much as it is usually supposed. Lloyd Gerson has attempted, rather compellingly, to show that Neoplatonists did not delude themselves into fancying that Aristotle's project is not openly opposing that of Plato. Both, for example, rejected nominalism and materialism. Aristotle agreed with Plato that 'there has to be something', a universal, an intelligible form, 'like humanity and whiteness for there to be particular human beings and particular white things'. His disagreement had to do with the alleged separation of forms (2005, p. 278). Certainly, Plato's forms are distinct from sensible particulars and properties. But being distinct does not necessarily entail being separate: forms cannot be thought to exist regardless of whether the corresponding sensible particulars exist or not; they are somehow tied with them. Aristotle, regarding forms as universals, argues that if we regard them also as separate, then forms would be both universals and individuals. His claim, however, that forms existing as separate are particulars, whereas they are thought of as being universals too, presupposes one assumption which he actually holds and makes him move a considerable, though not unbridgeable, distance away from Plato. The assumption in question is that universals cannot exist uninstatiated,[25] that particular entities are the primary substances, the real instances of intelligible objects, or that only through understanding the particulars can we understand the universals.

Yet, we must underline the fact that the endorsement of that assumption by no means leads to any revival of empiricism, as professed by the earlier cosmologists. By drawing philosophy back into the realm of the sensible world, into actuality, Aristotle assigned himself the task of transcending the limitations of Plato's philosophy without falling back into the old fallacious ways of empiricism. The

[25] Our short presentation, at this point, is based on Gail Fine's analysis, 1993, pp. 60–61.

cosmological tradition of the past could be filtered through a theory of knowledge capable to critically inspect all the dimensions of knowing itself, bringing them prominently into view as actual problems indispensable for any attempt to theorize on nature, and reversely the metaphysical and epistemological traditions of the present could be reterritorialized upon a landscape of actuality traversed not by simulations but by individual entities invested with their own reality. Aristotle does not draw rough lines of demarcation between the way of truth and the way of seeming. Contrary to that, whenever he is about to come to grips with the complexities of being, or thinking, or speaking, he reconstructs the arguments of the most influential philosophers preceding him. Neither does he set apart actuality from reality. Instead, he introduces a concept of matter as potentiality, as the field of non-actualized possibilities. From now on, change and plurality are problems that thought must not only embrace, as problems relevant to the knowledge of what-is, but also unavoidably explicate, because their impact on thought itself, on the way thought can articulate its reflective movement as thought of reality, aware of its being nonidentical with its object, cannot be repressed any more.

If Parmenides problematized what-is, Aristotle problematized both reality and actuality, going back and discussing seriously 'how is it possible for action and passion to occur', when do they occur, why and how (1955, p. 237, *On Coming-to-Be and Passing-Away*, 325[a], 23–26), and what account should we give for coming-to-be and passing-away. His criticism against the early atomists brought to the forefront questions involving the intersection of reality and actuality: the question how could we explain motion and what is its cause, or the question how could we understand the possibility of atoms' being and how could we justify the existence of entities which are mathematically divisible and at the same time physically indivisible, insofar as their 'ability to be mathematically divided entails the ability to be physically divided, even though the two abilities are very different logically, that is, in terms of their actualization' (Hasper 2006b, p. 124). The first question led Epicurus to modify the early atomic theory providing an explanation for the motion of atoms which employs, along with the principle of collisions, that of the weight of the atoms and the assumption that atoms falling down through the void occasionally and unpredictably swerve from their predetermined course and collide with each other (see O'Keefe 2005, p. 122). The second question triggered detailed discussions and heated debates on the fabric of cosmos for many centuries to follow. Perhaps even more weighing, on the whole development, in particular, of natural philosophy from the late medieval period up to the nineteenth century, is a third question addressed by Aristotle, in connection with the problems of motion and divisibility: How can there be any before and after without the existence of time? Or how can there be any time without the existence of motion? (Aristotle 1984, p. 130, *Physics*, VIII, 251[b], 10–12). To be in time, to become something and to pass away in time, the real expressed as actual in time, emerged as one of the most vexing problems thought had to tackle ever since. Aristotle's own answer was that time is 'just this – number of motion in respect of "before" and "after" … not movement, but only movement in so far as it admits of enumeration' (1984, p. 70, *Physics*, IV, 219[b], 2–3), and, indeed, enumeration is possible, because the 'now', the present being of the entity moving, can be posited as the measure of time (Routila 1980, p. 250). Time as a kind of number: How could we conceive Newton or Leibniz theorizing on nature without such a conceptual background?

Between Speculations and Propositions

The preceding analysis shows that Alan Chalmers is correct in underlining the distinctly speculative character of the ancient controversy over the atoms and the void. He is not correct, however, in presenting as a mark of differentiation, between the ancient speculative and the modern scientific versions of atomism, the fact that some of the properties which the early atomists ascribed to atoms 'had their origin in common sense', that their atoms were, in the last analysis, 'miniature idealized' colliding stones (Chalmers 2009, pp. 39–40). As we have tried to point out, the concepts of the atom and that of the void were the fruits of a deep problematization of common-sense intuitions. Any theory concerning natural phenomena draws on ordinary everyday experience, incorporates, or could be referred back to, intuitions that are part of ordinary experience. What really does make a significant difference is the answer to the question whether the theory under scrutiny transcends common sense, without entirely suppressing it, or idealizes, and thus vindicates, common sense. Leucippus' and Democritus' theory, we think, belongs rather to the first category. As a matter of fact, it was the first ancient Greek theory to be launched with the explicit or, if anything else, recognizable purpose of doing precisely that moving beyond the limits of ordinary experience, but without negating what ordinary experience confirms. The Parmenidean core distinctions, that between the way of seeming and the way of truth, as well as that between what-is and what-is-not, are nested inside early atomism. 'All the perceptible qualities are brought into being, relative to us who perceive them, by the combination of atoms, but by nature nothing is white or black or yellow or red or bitter or sweet [...] People think of things as being white and black and sweet and bitter and all the other qualities of that kind, but in truth 'thing' and 'nothing' is all there is [...] 'thing' being [Democritus'] name for the atoms and 'nothing' for the void'.[26] This testimonium given by Galen of Pergamum illustrates how Parmenides' doctrine of being was converted into the first system of mechanical materialism, wherein we can trace the origins of a conception of nature which still retains its currency. We owe to Democritus, as Ernst Bloch notes, the definition of nature as a 'subject-free objectivity' (Bloch 1985, p. 83), as an *external* world, lying beyond our perceptual grasp, independent of human agency, and visible only to the eyes of the mind. But the surviving fragments and testimonia about Democritus' theory are also highly indicative of the major difficulty that any such endeavour to define nature as stripped of sensible

[26] Fr 68A49, Diels and Kranz (1960, II, p. 97). Translation by Taylor (1999, pp. 143–144).

qualities is doomed to go through. The eyes of the mind must somehow correspond or relate to the eyes of the body. Again quoting Galen, 'Democritus was aware of this; when he was attacking the appearances with the words 'By convention colour, by convention sweet, by convention bitter, but in reality atoms and void' he made the senses reply to thought as follows: 'Wretched mind, you get your evidence from us, and yet you overthrow us? The overthrow is a fall for you''.[27] Only by being active, thought can penetrate the veil of appearances. In order to remove the traces of the sensible, though, it must also be objective, to detach itself from the body, the locus of sensibility that made thinking possible in the first place. If truth is that which it pursues, then thought should not function as a mirror of the sensible, but still it should function as a mirror of the visible, external world, of what-is independently of any human mediation.

The conceptual vacillation of Democritus between the sensible and the intelligible, which is evident in most of his fragments, either ethical, psychological, or epistemological (according to our late modern classificatory schemes), cannot be resolved because in his theory of knowledge, as is the case with all ancient theories of knowledge, there is no space reserved for the subjective factor, as a crucial, indispensible element in the production of knowledge (Bloch 1985). Knowing is always a kind of seeing, a way of viewing things from a distance, not a kind of working on things, of imitating nature by setting up, controlling, and reproducing definite processes. In this lack of experimentation (which exemplifies the contempt for labour shared by the members of the ruling class in the slave-owning mode of production) lies the difference between early atomism and modern atomism. We agree with Chalmers up to that point. But we believe that this difference separates Democritus from Boyle, too. From the fact that the latter's corpuscularianism was not experimentally tested, it does not follow that the philosophical import it had is more comparable with that of Democritus' atomism than with that of the twentieth-century scientific atomism.

Modern science is not a by-product of ancient philosophy. And reversely, ancient or early modern philosophy should not be reduced into what we now consider science to be. But both the terms 'science' and 'philosophy' bear significations liable to appreciable alterations, as time goes by. If we define science, taking into consideration only its presently dominant form, as a set of institutionalized practices, a standardized way of conducting experiments within the secluded social space of laboratory, coupled with a way of formulating problems within the equally secluded social space of academic training facilities, then Parmenides' and Aristotle's speculations are irremediably alien not only to the modern atomic theory but to any present-day scientific undertaking. If, by contrast, we define science as a tradition of posing interesting questions, testing hypotheses, and correcting the unavoidably many mistakes through critical discussion, then those speculations can be seen, or more precisely can be reappropriated, as part of that tradition. But they should not be represented as the simplistic, elementary versions of the elaborate and specific

[27] Fr 68B125, Diels and Kranz (1960, II, p. 168). Translation by Taylor (1999, p. 143).

propositions which are included in the contents of knowledge we presently possess. Chalmers rightly underscores the importance of this difference as far as science education is concerned. The atomisms of the past should be reconstructed and presented as complex theoretical accounts, whose difference from the complex theoretical accounts of late modernity might cultivate the ability to discern, and criticize, the earmarks of modern scientific experimental culture. Still, we could also add that there is yet another advantage in opening space for the history of early atomism in science education, namely, the awareness that knowing involves a conceptual work, and that between concepts and sensible things, a grey zone always lurks, of polysemous entities, tentative constructions, projections, vacillations, and unstable associations. The existence of this grey zone is what makes science to be something more than a mirror of reality: an adventure of intervening in the world so as to make it better. We are far away, indeed, from Parmenides. But Parmenides' open question of what is 'to be' is still relevant to the task of defending science as a critical tradition. Should we regard the distance separating our present from that past as an impassable gap, then we should also wonder how much distance have we already traversed, away from what Otto Neurath and his colleagues, back in 1929, envisaged (in Vienna Circle's Manifesto, Neurath 1981): a scientific conception of what-is; a quest of knowing presupposing the collective labour of inquirers and rendering the real possibilities for a better common life objective, actually available to every human being; and a genuinely philosophical undertaking within the sciences, which was not intended, though, to be yet another version of philosophy, as we now habitually understand this term, as the science of the sciences or as the clarification of scientific statements.

Acknowledgements We would like to thank Alexandra Halkias for reading an early draft of the article and providing us with helpful comments.

References

Aerts, D. (1981). *The one and the many: Towards a unification of the quantum and classical description of one and many physical entities.* Doctoral dissertation, Brussels Free University, Brussels.

Aristotle. (1955). *On sophistical refutations/on coming-to-be and passing-away/on the cosmos* (E. S. Forster & D. J. Furley, Trans.). Cambridge, MA/London: Harvard University Press.

Aristotle. (1961). *Metaphysics* (H. Tredennick, Trans.). Cambridge, MA: Harvard University Press.

Aristotle. (1984). Physics (R. P. Hardie & R. K. Gaye, Trans.). In J. Barnes (Ed.), *The complete works of Aristotle*. Princeton: Princeton University Press.

Barnes, J. (1982). *The Presocratic philosophers*. London/New York: Routledge.

Bedu-Addo, J. T. (1983). Sense-experience and recollection in Plato's Meno. *American Journal of Philology, 104*(3), 228–248.

Bloch, E. (1985). *Leipsiger Vorlesungen zur Geschichte der Philosophie 1950–1956, Band I: Antike Philosophie*. Frankfurt am Main: Suhrkamp Verlag.

Bohm, D., & Hiley, B. J. (1993). *The undivided universe: An ontological interpretation of quantum mechanics*. London/New York: Routledge.

Calogero, G. (1977). *Studi sull' Eleatismo*, nuova edizione. Firenze: La Nuova Italia.
Chalmers, A. F. (1998). Retracing the ancient steps to atomic theory. *Science Education, 7*(1), 69–84.
Chalmers, A. F. (2009). *The scientist's atom and the philosopher's stone: How science succeeded and philosophy failed to gain knowledge of atoms, (Boston studies in the philosophy of science, 279)*. Dordrecht/Heidelberg/London/New York: Springer.
Cordero, N.-L. (1979). Les deux chemins de Parménide dans les fragments 6 et 7. *Phronesis, 24*(1), 1–32.
Cordero, N.-L. (2004). *By being, it is: The thesis of Parmenides*. Las Vegas: Parmenides Publishing.
Coxon, A. H. (1986). *The fragments of Parmenides*: *A critical text with introduction and translation. Phronesis*, Suppl. 3. Assen: Van Gorcum.
Curd, P. (2004). *The legacy of Parmenides: Eleatic monism and later Presocratic thought*. Las Vegas: Parmenides Publishing.
Dayley, J. (2006). Democritus' Parmenidean influence. *Aporia, 16*(2), 51–60.
de Ronde, C., & Christiaens, W. (Eds.). (2010). Metaphysical issues in quantum mechanics. Thematic issue of *Philosophica*, *83*(1).
de Vogel, C. J. (1988). *Rethinking Plato and Platonism*. Leiden/New York/København/Köln: Brill.
Diels, H. (1897). *Parmenides'Lehrgedicht – Griechisch und Deutsch*. Berlin: Druck und Verlag von Georg Reimer.
Diels, H., & Kranz, W. (Hrgs.). (1960). *Die Fragmente die Vorsokratiker*, neunte Auflage. Berlin-Neukölln: Weidmannsche Verlagsbuchhandlung.
Ferwerda, R. (1972). Democritus and Plato. *Mnemosyne, 25*(4), 337–378.
Fine, G. (1993). *On ideas: Aristotle's criticism of Plato's theory of forms*. Oxford: Clarendon.
Fränkel, H. (1946). [Review of *Parmenides*: *Some comments on his poem*. By Willem Jacob Verdenius. Groningen: J. B. Wolters' Uitgevers-Maatschappij, 1942]. *Classical Philology*, *41*(3), 168–171.
Furley, D. J. (1967). *Two studies in the Greek atomists*. Princeton: Princeton University Press.
Gallop, D. (1984). *Parmenides of Elea: Fragments – A text and translation with an introduction*. Toronto/Buffalo/London: University of Toronto Press.
Gerson, L. (2005). *Aristotle and other Platonists*. Ithaca/London: Cornell University Press.
Harman, P. M. (1988). *The natural philosophy of James Clerk Maxwell*. Cambridge: Cambridge University Press.
Hasper, P. S. (2006a). Zeno unlimited. *Oxford Studies in Ancient Philosophy, 30*, 49–85.
Hasper, P. S. (2006b). Aristotle's diagnosis of atomism. *Apeiron: A Journal for Ancient Philosophy and Science, 39*(2), 121–155.
Hassing, R. (2003). Leibniz without physics. *The Review of Metaphysics, 56*(4), 721–761.
Havelock, E. A. (1958). Parmenides and Odysseus. *Harvard Studies in Classical Philology, 63*, 133–143.
Heidegger, M. (1992). *Parmenides* (A. Schuwer & R. Rojcewicz, Trans.). Bloomington/Indianapolis: Indiana University Press.
Hoffmann, E. (1964). Der historische Ursprung des Satzes vom Widerspruch [1923] (Reprinted in idem). In *Drei Schriften zur greichischen Philosophie* (pp. 53–64). Heidelberg: Heidelberger Akademie der Wissenschaften.
Izquerdo-Aymerich, M., & Adúriz-Bravo, A. (2009). Physical construction of the chemical atom: Is it convenient to go all the way back? *Science Education, 18*(3–4), 443–455.
Justi, R., & Gilbert, J. (2000). History and philosophy of science through models: Some challenges in the case of the atom. *International Journal of Science Education, 22*(9), 993–1009.
Kahn, C. H. (1966). The Greek verb 'to be' and the concept of being. *Foundations of Language, 2*(3), 245–265.
Kahn, C. H. (1969). The thesis of Parmenides. *The Review of Metaphysics, 22*(4), 700–724.
Karsten, S. (1835). *Philosophorum Graecorum Veterum praesertim qui Ante Platonem Floruerunt Operum Reliquiae – Volumen I, Pars Altera, Parmenides*. Amstelodami: sumtibus J. Müller & Soc.
Kirk, G. S., Raven, J. E., & Schofield, M. (1983). *The Presocratic Philosophers* (2nd ed.). Cambridge: Cambridge University Press.

Leibniz, G. W. (1988). *Discourse on metaphysics and related writings* (R. Niall, D. Martin, & Stuart Brown, Ed. & Trans.). Manchester: Manchester University Press.

Mansfeld, J. (1964). *Die Offenbarung des Parmenides und die Mensliche Welt*. Assen: Van Gorcum.

Marcinkowska-Rosół, M. (2010). *Die Konzeption des, noein' bei Parmenides von Elea*. Berlin/New York: De Gruyter.

Matthews, M. R. (2009, September). Review of A. Chalmers' *The scientist's atom and the philosopher's stone* (pp. 15–32). *Newsletter of the IHPST Group*. http://ihpst.net/newsletters/sept2009.pdf

Maxwell, J. C. (1890). Atom. In *Encyclopaedia Britannica* (9th ed., Vol. 3) (Reprinted in *The scientific papers of James Maxwell,* pp. 445–484, by W. D. Niven, Ed., 2 vols, 1875, Cambridge: Cambridge University Press).

Maxwell, J. C. (1990). Inaugural Lecture at Marischal College, Aberdeen, 3 November 1856. In P. M. Harman (Ed.), *The scientific letters and papers of James Clerk Maxwell* (Vol. 1: 1846–1862 pp. 419–431). Cambridge: Cambridge University Press.

McCabe, M. M. (1994). *Plato's individuals*. Princeton: Princeton University Press.

Miller, D. (2003). *The Third Kind in Plato's Timaeus, (Hypomnemata, 145)*. Göttingen: Vandenhoeck & Ruprecht.

Mourelatos, A. P. D. (2008). *The Route of Parmenides* (Rev. and expanded ed.). Las Vegas/Zurich/Athens: Parmenides Publishing.

Nehamas, A. (1979). Self-predication and Plato's theory of forms. *American Philosophical Quarterly, 16*(2), 93–103.

Nehamas, A. (1999). On Parmenides' three ways of inquiry (Reprinted in idem, 1981). In *Virtues of authenticity: Essays on Plato and Socrates* (pp. 125–137). Princeton: Princeton University Press.

Neurath, O. (1981). Wissenschaftliche Weltauffassung Der Wiener Kreis. In R. Haller & H. Rutte (Hg.), *Otto Neurath*: *Gesammelte Philosophische und Methodologische Schriften*, Bd. I (pp. 299–336). Wien: Hölder-Pichler-Tempsky.

O'Keefe, T. (2005). *Epicurus on freedom*. Cambridge: Cambridge University Press.

Owen, G. E. L. (1957–1958). Zeno and the mathematicians. *Proceedings of the Aristotelian Society*, New Series, *58*, 199–222.

Owen, G. E. L. (1960). Eleatic questions. *The Classical Quarterly, 10*(1), 84–102.

Palmer, J. (2009). *Parmenides and Presocratic philosophy*. Oxford: Oxford University Press.

Piron, C. (1983). Le Réalisme en Physique Quantique: une Approche selon Aristote. In E. Bitsakis (Ed.), *The concept of physical reality: Proceedings of a conference organized by the Interdisciplinary Research Group, University of Athens, 1982* (pp. 169–173). I. Zacharopoulos: Athens.

Plato. (1955). *Phaedo.* Translated with introduction and commentary by R. Hackforth. Cambridge: Cambridge University Press.

Plato. (1972). *Phaedrus.* Translated with introduction and commentary by R. Hackforth, Cambridge: Cambridge University Press.

Plato. (2000a). *Timaeus* (D. J. Zeyl, Trans.). Indianapolis/Cambridge: Hackett Publishing Company.

Plato. (2000b). *The Republic* (G. R. F. Ferrari, Ed. & T. Griffith, Trans.). Cambridge: Cambridge University Press.

Popper, K. (1992). Quantum theory and the schism in physics. In W. W. Bartley III (Ed.), *The postscript to the logic of scientific discovery*. London/New York: Routledge.

Popper, K. (1998). *The world of Parmenides*: *Essays on the presocratic enlightenment* (A. F. Petersen, Ed., with the assistance of Jørgen Mejer). London/New York: Routledge.

Prauss, G. (1966). *Platon und der logische Eleatismus*. Berlin: Walter de Gruyter & Co.

Pyle, A. (1995). *Atomism and its critics: From Democritus to Newton*. Bristol: Thoemmes Press.

Reinhardt, K. (1916). *Parmenides und die Geschichte der Griechischen Philosophie*. Bonn: Friedrich Cohen.

Richard, M. K. (2010). *Philosophy before Socrates: An introduction with text and commentary* (2nd ed.). Indianapolis: Hackett Publishing.

Rodríguez, M. A., & Niaz, M. (2002). How in spite of the rhetoric, history of chemistry has been ignored in presenting atomic structure in textbooks. *Science Education, 11*(5), 423–441.
Rodríguez, M. A., & Niaz, M. (2004). A reconstruction of structure of the atom and its implications for general physics textbooks: A history and philosophy of science perspective. *Journal of Science Education and Technology, 13*, 409–424.
Routila, L. (1980). La Définition Aristotélicienne du Temps. In P. Aubenque (dir.), *Concepts et Catégories dans le Pensée Antique* (pp. 247–252). Paris: Libraire Philosophique J. Vrin.
Tarán, L. (1965). *Parmenides: A text with translation, commentary, and critical essays*. Princeton: Princeton University Press.
Tarán, L. (1977). [Review of Alexander P. D. Mourelatos: The *Route of Parmenides*, New Haven/London: Yale UP 1970]. *Gnomon*, *49*(H. 7), 651–666.
Taylor, C. C. W. (1999). *The atomists, Leucippus and Democritus: Fragments – A text and translation with a commentary*. Toronto/Buffalo/London: University of Toronto Press.
Verelst, K., & Coecke, B. (1999). Early Greek thought and perspectives for the interpretation of quantum mechanics: Preliminaries to an ontological approach. In G. C. Cornelis, S. Smets, & J. P. Van Bendegem (Eds.), *Metadebates on science: The blue book of 'Einstein Meets Magritte'* (pp. 163–195). Dordrecht/Brussels: Kluwer/VUB-Press.
Vlastos, G. (1967). Zeno of Elea. In P. Eduard (Ed.), *Encyclopedia of philosophy* (pp. 369–379). New York/London: The Macmillan Company & The Free Press/Collier-Macmillan Unlimited.
Wilkinson, L. A. (2009). *Parmenides and to eon: Reconsidering Mythos and logos*. London/New York: Continuum.

Toward a Scientifically Sound Understanding of Concepts of Matter

Georgios Tsaparlis and Hannah Sevian

In this concluding chapter, we offer a review of perspectives presented in each of the parts in the volume, organized somewhat differently from the order of the chapters in the book. Our purpose is twofold: (i) to emphasize the features, qualities, and strengths of the works presented and, (ii) where appropriate, to highlight areas of convergence and of potential dissonance that might bring to light compelling questions for future study. As an ultimate aim of research on teaching and learning is to improve education, it is hoped that the analysis and synthesis presented here may offer guidance toward that end.

History and Philosophy of Science: Ancient and Modern Controversies About the Concept of Matter and Atomism

Leucippus and Democritus	ΛΕΥΚΙΠΠΟΣ ΚΑΙ ΔΗΜΟΚΡΙΤΟΣ
Consider as basic elements (*stoicheia*)	*ΣΤΟΙΧΕΙΑ*
The complete (*plēres*) and the void (*kenon*)	ΤΟ *ΠΛΗΡΕΣ* ΚΑΙ ΤΟ *ΚΕΝΟΝ* ΕΙΝΑΙ ΦΑΣΙ
The first one existent/what-is (*on*)	ΤΟ ΜΕΝ *ΟΝ* ΤΟ ΔΕ *ΜΗ ΟΝ*
The second one nonexistent/what-is-not (*mē on*)	
One filled (*plēres*) and solid (*stereon*)	ΤΟ ΜΕΝ *ΠΛΗΡΕΣ* ΚΑΙ *ΣΤΕΡΕΟΝ*
The other empty (*kanon*) and thin (*manon*)	ΤΟ ΔΕ *ΚΑΝΟΝ* ΚΑΙ *ΜΑΝΟΝ*
These two are the causes (*aetia/etia*) of what exists/what-is (*on*) as matter (*hylē*)	*ΑΙΤΙΑ* ΔΕ ΤΩΝ *ΟΝΤΩΝ* ΤΑΥΤΑ ΩΣ *ΥΛΗ*
Aristotle, *METAPHYSICA*	ΑΡΙΣΤΟΤΕΛΗΣ, *ΜΕΤΑ ΤΑ ΦΥΣΙΚΑ*
Α΄ 4.985β4	Α΄ 4.985β4

G. Tsaparlis
Department of Chemistry, University of Ioannina, Ioannina, Greece
e-mail: gtseper@cc.uoi.gr

H. Sevian (✉)
Department of Chemistry, University of Massachusetts, Boston, MA, USA
e-mail: Hannah.Sevian@umb.edu

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5_23,

Introduction

Ancient philosophers dealt with the explanation of worldly matters and their reduction to a common principle. Leucippus, Democritus, and Epicurus advocated the particulate/corpuscular nature of matter through an *atomic theory*. They declared *atoms* as the essence of objects, having their own weight and moving in empty space (the *void*). Their *union* results in the *synthesis* of all objects, while their *breaking apart* results in the *disintegration* of that which exists (*of what-is*). The atoms of ancients are so small that they are invisible; they are unborn, permanent, and indestructible, of the same kind but varying in size, weight, and shape, changing only their position and configuration. Equally revolutionary as the concepts of *atoms-molecules* was the concept of *void* because one needs the void if one should allow atoms-molecules to move (Nussbaum 1998, p. 176). The ancient atomic theory was neglected for centuries, only to return to the foreground in the early 1800s, and after considerable debate, it became a rigorous, exact, and aesthetically pleasing theory.

Investigating the Historical Development of the Concept of Matter

Skordoulis and Koutalis (chapter "Investigating the Historical Development of the Concept of Matter: Controversies About/In Ancient Atomism", this volume) argue that "science educators should consider that the History of Atomism and its position in the History of Science is still a matter of debate." In particular, the authors refer to Chalmers' (2009) book, in which he surveys the history of atomism from Democritus to the twentieth century. For Chalmers, ancient atomism, as an *ontological position* (a philosophical theory of the composition of bodies), had little, if anything, to do with the *experimentally supported* modern general atomic theory of matter: "The properties of atoms were discovered by experiment rather than philosophical analysis. The modern atom has an internal structure, most importantly an electron structure" (Chalmers 2009, p. 262). In this chapter, the authors, while accepting that Chalmers "is correct in underlining the distinctly speculative character of the ancient controversy over the atoms and the void," assert that Chalmers is not correct, however, in presenting as a mark of differentiation, between the ancient speculative and the modern scientific versions of atomism, the fact that some of the properties which the early atomists ascribed to atoms "had their origin in common sense," that their atoms were, in the last analysis, "miniature idealized" colliding stones (Chalmers 2009, pp. 39–40). For the authors, Leucippus' and Democritus' theory "was the first ancient Greek theory to be launched with the explicit or, if anything else, recognizable purpose of… moving beyond the limits of ordinary experience, but without negating what ordinary experience confirms." In modern science, the main role of theory is to organize experimental facts, but "the theoretical rationale in which the experiment is conducted can be even more important than the experiment itself" (Niaz and Rodriguez 2000, p. 319).

Of particular interest is the authors' discussion about Parmenides' and Aristotle's philosophical theories. Parmenides stated a theory of being, dealing with "what-is" and distinguishing between truth and appearance. Aristotle dealt with both reality and actuality, discussing "how is it possible for action and passion to occur," when do they occur, why and how, and what account should we give for coming-to-be and passing-away. Aristotle criticized early atomists bringing to the forefront questions involving the intersection of reality and actuality: "How could we explain motion and what is its cause?" or "How could we understand the possibility of atoms' being, and could we justify the existence of entities which are mathematically divisible and at the same time physically indivisible?" – insofar as their "ability to be mathematically divided entails the ability to be physically divided, even though the two abilities are very different logically, that is, in terms of their actualization" (Hasper 2006, p. 124). For the authors of this chapter, "if we define science as a tradition of posing interesting questions, testing hypotheses and correcting the unavoidably many mistakes through critical discussion, then Parmenides' and Aristotle's speculations can be seen, or more precisely can be re-appropriated, as part of that tradition." Finally, "there is yet another advantage in opening space for the history of early atomism in science education, namely, the awareness that knowing involves a conceptual work…and that between concepts and sensible things a grey zone always lurks, of polysemous entities, tentative constructions, projections, vacillations, and unstable associations. The existence of this grey zone is what makes science to be something more than a mirror of reality: an adventure of intervening in the world so as to make it better. We are far away from Parmenides. But Parmenides' open question of what is 'to be' is still relevant to the task of defending science as a critical tradition."

Learning Progressions for Teaching a Particle Model of Matter

Learning progressions (LPs) are empirically validated descriptions of pathways taken by students, over extended periods of time, toward achieving an *upper anchor* of scientific knowledge and/or practice. According to Wiser, Frazier, and Fox (chapter "At the Beginning Was Amount of Material: A Learning Progression for Matter for Early Elementary Grades", this volume), a learning progression for matter (LPM) "describes the interrelated conceptual changes (about material, weight, volume, matter and its transformations) as well as epistemological ones that constitute the reconceptualization of matter at the macroscopic and submicroscopic levels. It also specifies in what order and combinations conceptual changes could potentially be achieved, including what key learning experiences are likely to be necessary. Thus, the LPM is a bridge between young children's ideas and a macroscopic/submicroscopic understanding of matter that is scientifically sound." Recently, Duschl et al. (2011) contributed a comprehensive analytical review of LPs in science (see chapter "Implicit Assumptions and Progress Variables in a Learning Progression About Structure and

Motion of Matter", by Sevian and Stains, this volume, for a summary of some of the findings). The four chapters in this part of the volume illustrate some of the variations identified by Duschl et al. in their analysis, including how the boundaries of the LP are defined, how intermediate levels are studied, and the explicit or implicit model of conceptual change associated with the LP. For example, Wiser et al. and Merritt and Krajcik differ in their definitions of LP, in terms of their tie to curriculum.

At the Beginning Was Amount of Material

Wiser, Frazier, and Fox (chapter "At the Beginning Was Amount of Material: A Learning Progression for Matter for Early Elementary Grades", this volume) propose an LPM for early elementary grades. For these authors, the study of an LP is inseparable from curriculum because the *reconceptualizations* of students and how they occur is embedded in what and how students learn. A reconceptualization is a "deep and fundamental reorganization of the large network of knowledge relevant to understanding." Theoretical constructs in their LPM are *core concepts* and *lever concepts*. Core concepts are not just the concepts involved in defining matter scientifically (e.g., mass); they are also concepts, such as weight, that play a conceptual role in students' progressing toward a scientific understanding of matter: many young students believe that atoms and molecules, as well as very small pieces of any material, do not have weight because "they feel like nothing." This belief alone makes the atomic model problematic for young students: if tiny things weigh nothing, matter cannot be made exclusively of atoms. Indeed, many students envision atoms as embedded in "stuff." Examples of core concepts are, on the one hand, *mass*, *volume*, *density*, *and states of matter* (for the scientific theory itself) and, on the other hand, *material*, *amount of material*, *weight*, *size*, *and particle* (for learning the scientific theory). Examples of lever concepts are *object*, *nonsolid*, and *size* (for Grades K-2); *material*, *amount of material*, *weight*, and *size* (for Grades 3–4); and *solid* and *liquid materials*, *particle*, and *heavy for size* (for Grade 5). A core concept remains a lever concept for some time, depending on how long the reconceptualizations take.

Wiser and her colleagues used Anderson's terminology (Mohan et al. 2009) in referring to young children's ideas as the *lower anchor* of the LPM. They situate their LPM as part of a K-12 matter LP for which the *upper anchor* is the atomic theory. Thus, they prefer thinking of the end point of the LPM as the Grade 5 stepping stone toward the atomic-molecular theory. They also refer to the state of the system at the end of Grade 2 as the Grade 2 stepping stone. A *stepping stone* is a new state of "relative equilibrium" in which the "content and structure are radically different from the previous stepping stone [and]… conceptually closer to the scientific theory than the lower anchor." In their chapter, the authors list the core concepts in the lower anchor, the Grade 2 stepping stone and the Grade 5 stepping stone. Finally, they report on a small-scale pilot study with kindergarteners and preschoolers, which indicated that a teaching intervention based on the LPM can improve young children's *amount conservation* and their ability to apply the *material construal* to *solid objects* in a very short period of time (2 weeks). In their overall conclusion, Wiser and her colleagues maintain that "in a full K-2 curriculum, students would explore a range of aggregates and liquids…[this] would establish a bridge between their intuitive quantification of non-solids (bigness [of a sample]) and their quantification of solid objects (counting) and pave the way to quantifying amounts of solid samples" (by dividing them into equal pieces, as is the case with LEGO™ blocks). Using a scale, they would discover that liquids have weight, contrary to what they thought initially, and that it is related to amount. The conceptual changes would be part of the development of two ontological categories: *material* and *matter*. The reconceptualization of matter is very complex – it involves a large number of small but coordinated steps and many kinds of conceptual changes: coalescences, differentiations, generalizations, more stringent specifications, breaking some old links, and creating new ones. Such reconceptualization is inevitably slow. It requires the support of curricula with a long time span that give ample time to revisit relations between concepts many times, in broader and broader contexts, and in relation to more sophisticated epistemological knowledge.

How Students' Understanding of a Particle Theory Develops

Johnson (chapter "How Students' Understanding of Particle Theory Develops: A Learning Progression", this volume) presents findings related to the particle theory from the results of a large-scale, cross-sectional assessment of views of the particle nature of substances held by middle school-aged students (Johnson and Tymms 2011) in relation to an LP that he previously determined through a 3-year, longitudinal, interview-based study. The LP (Johnson 1998), and a companion paper later (Johnson 2005) in which he reflects on the methodological features of the approach, describes the progression of student learning from holding a view that matter is continuous to three possible, more sophisticated end points: Model A, in which the particles are in the continuous substance; Model B, in which the particles are the substance, but they have macroscopic character; and Model C, in which the particles are the substance and they do not have macroscopic character. These views also take into consideration how students conceive of the forces between particles and the motion of the particles. Johnson reports on the use of the Rasch model to determine whether a large set of data from fixed-response items could fit student data to the LP.

The LPs of Wiser et al. (chapter "At the Beginning Was Amount of Material: A Learning Progression for Matter for Early Elementary Grades", this volume) and of Johnson (chapter "How Students' Understanding of Particle Theory Develops: A Learning Progression", this volume) might be considered in sequence, for if the fifth grade stepping stone of Wiser and colleagues corresponds to the lower anchor of Johnson, that matter is continuous, then a landscape of pathways through intermediate understandings emerges. However, there are at least two criteria that must be taken into consideration in this interpretation. First, the next stopping point should involve reconceptualization. Second, in order to serve as a stepping stone, i.e., an intermediate understanding that is productive for the advancement of learning, it should be "conceptually closer to the scientific theory than the lower anchor." In fact, Wiser and colleagues have argued that Johnson's Models B and C may be such stepping stones, but model A is not, because it does not meet these criteria. This has important implications for the LP examined by Sevian and Stains (chapter "Implicit Assumptions and Progress Variables in a Learning Progression About Structure and Motion of Matter", this volume).

Implicit Assumptions in a Learning Progression about Structure and Motion of Matter

Sevian and Stains (chapter "Implicit Assumptions and Progress Variables in a Learning Progression About Structure and Motion of Matter", this volume) demonstrate a cycle of validation of the structure and motion of matter, part of a larger LP on chemistry for Grade 8 (age 13) through graduation from university. They show that measurable progress variables in the LP can be identified through characterization of students' applications of implicit assumptions (IAs) to reasoning about a phenomenon and that this method can differentiate among the IAs. IAs act as cognitive constraints, shaping and limiting the ways in which a person reasons. By creating an assessment that probes a student's thinking in the context of a phenomenon that causes the student to generate an instantaneous mental model used to reason, it is possible to unpack the IAs that constrained the mental model, and it is also possible to determine variables along which progress can be observed. Sevian and Stains take, as their initial theory of cognition, the LP of Talanquer (2009), which characterizes learning in terms of the evolution of IAs.

The PNM dimension of Talanquer's corresponds in large part to the LP of Johnson and takes as its lower anchor an IA that matter is thought to be a continuous medium with granules of substance embedded in the medium. This evolves to a corpuscular view of matter, as consisting of distinct substances, in which empty space exists between particles. Sevian and Stains observed this distinction, in the context of a gas phase diffusion phenomenon, in several instantiations of the IAs in the progress variable on trajectories of particles. For example, nearer to the lower anchor, they found that students combined the continuous assumption about the structure of matter with a static assumption of dynamics (particles are fixed in space) to reason that particles do not move by themselves, but instead air (as wind or breeze) controls their trajectories. They also found that when a continuous assumption was combined with a causal-dynamic assumption about dynamics (the movement of particles occurs as a result of an external force, without which movement would cease), students held the view that particles traveled by avoiding macroscopic obstacles such as air masses or regions of different density. Perhaps these two outcomes are illustrative of ways that students would reason if they held Models A (particles are in the continuous substance) and B (particles are the substance, but they have macroscopic character) of Johnson. If Wiser's assertion that Johnson's Model B is a stepping stone but Model A is not, then a transition to Model B must involve a reconceptualization, while a transition to Model A would not. It is possible, then, that Talanquer's IAs could account for this, as Johnson's lower anchor relies on an IA that matter is continuous, and this is unchanged whether there is a view that air controls the trajectories of solute particles or that particles travel so as to avoid macroscopic obstacles. However, in the latter case, a student's IAs include a view of dynamics as causal-dynamic rather than static, and perhaps this is the reconceptualization.

This is, of course, a speculation, but it illustrates the potential to learn from places where these research programs intersect and to ask new questions that could push knowledge forward in ways that could have profound effects on practice. For if a well-researched sequence of stepping stones were uncovered and agreed upon by multiple research programs, along with a carefully tested sequence of learning experiences that allows students to pass through these stepping stones, then it would mark a significant advancement in the pedagogy of the possible.

Supporting Students in Building a Particle Model of Matter

Merritt and Krajcik (chapter "Learning Progression Developed to Support Students in Building a Particle Model of Matter", this volume) present findings from empirical tracking of sixth grade students (ages 11–12) along a progress variable of the particle model of matter (PMM), which was "developed to determine how student understanding of the PNM changes during instruction" in relationship to the sixth grade chemistry unit in the Investigating and Questioning our World through Science and Technology (IQWST) curriculum (Merritt et al. 2012). The authors emphasize that "learning progressions are not developmentally inevitable (Stevens et al. 2010) nor are they tied to a particular curriculum, but do depend on instruction … the order in which ideas are presented and built upon during instruction are factors in how learning progresses." Thus, they investigate how students' ideas evolve over time as a function of instruction. This is accomplished through tracking students' building of the particle model over time by a PMM progress variable that encompasses varying starting points (descriptive models) and ending points (toward a complete particle model). The progress variable measures progress along a concept map that reflects increasingly sophisticated understanding. The instruction occurs in the context of one unit of the IQWST curriculum, which was designed with considerable care (described in the chapter) and in alignment with existing science standards in the USA. This chapter, which represents a small portion of the larger study to develop the curriculum with teacher input alongside the development and validation of the progress variable, reports on the use of the PMM progress variable to track the learning of 122 sixth grade students, in three different teachers' classes, and was intended also to provide insight into how the teachers' instructional strategies supported students' development of the PNM.

Results of the study indicate a trend of increasing sophistication in students' understanding of the PNM, with students clearly progressing from "mixed" models, to "basic" models and reaching understanding of a "complete" model as the unit progresses. The validated measures, including scoring guides, will serve as invaluable resources to teachers as they track student progress and provide feedback to students in future. The authors also make a strong case that the validated progress variable and measures will now permit more detailed observations of instruction to determine links between instruction and assessment, in order "to obtain a complete picture of how closely teachers are following the curriculum, what modifications they make to the curriculum and how they utilize the embedded assessments to inform their practice, evaluate student progress and provide feedback to students." In the context of the three LP chapters reviewed above, we add that such an effort may also shed light on the question of the extent to which LPs are dependent on (or inseparable from) curriculum.

Chemical Reactions, Chemical Phenomena

The study of substances, their reactions and syntheses, and their properties lies at the heart of chemistry. In essence, a chemist is a scientist who is knowledgeable about the properties and transformations of substances (Basolo 1984). According to Nelson (2003), substances can undergo three kinds of changes: *physical*, *physicochemical*, and *chemical*. Properties relating to the three kinds of changes are likewise called physical, physicochemical, and chemical. The first two kinds of categories are usually conflated, but it is very useful to chemists to distinguish between them. Changes are also called *phenomena*. Tsaparlis (2003) points out that a chemical phenomenon involves one or more chemical reactions and at the same time may involve several physical and physicochemical phenomena. The concept of substance is central in these definitions. Deep conceptual understanding of this concept, and consequently of the concepts of chemical changes and reactions, has to wait until the concepts molecules, atoms, and ions are introduced and understood well enough. This is consistent with Wiser and her colleagues' (chapter "At the Beginning Was Amount of Material: A Learning Progression for Matter for Early Elementary Grades", this volume) idea of an LP.

Explanations of Chemical Changes for Young Students in Terms of Simple Particle Models

Papageorgiou (chapter "Can Simple Particle Models Support Satisfying Explanations of Chemical Changes for Young Students?", this volume) asks if simple particle models can support satisfying explanations of chemical changes for young students. A satisfying explanation (from the student's perspective) of a chemical change is not something that is stable, since it depends on the corresponding model that is used at school level. In addition, explanations of chemical changes can also vary in accordance to the educational level of the learner. There is a significant number of models that support explanations of chemical changes; they have been developed or studied for particular educational levels. Papageorgiou has categorized these models and the explanations that are based on them under three very general levels. At the first level, the "atom" model is an important kind of particle and the "bond" model is a kind of holding between atoms. At the second level, the following models are used: representation of the structure of the atom (electronic configuration) as nucleus and electron shells based on the Bohr model; the "ion" model; "molecular" or "non-molecular" substances; and covalent, ionic, metallic, etc. bonds. At the third level, atomic and molecular orbitals are introduced. The first level is probably the most important one in educational terms, due to the fact that this is the level of pupils' first engagement with the concept of chemical change and so forms the foundation for the next levels; it also affects the development of pupils' concepts of chemical change at the next levels. Even at the first level, the models are particle models, associated with the concept of "substance" (Johnson 2002) and not with the general idea of "matter." The design of such models has, as a precondition, the establishment of the concept of substance and the clear distinction between "substance" and "mixture." Particles are particles of a particular substance, not particles in general. The particle model can help students explain chemical changes on the basis of the changes of bonds: *during chemical changes both formation and destruction of bonds happen*. The introduction of explanations to young students in the context of the first level has the advantage of exposing them to the relevant concepts over a longer school time.

Implicit Assumptions in Students' Reasoning About Substances and Reactions

Talanquer (chapter "How Do Students Reason About Chemical Substances and Reactions?", this volume) considers crucial that students understand the relationship between the physical and chemical properties of substances and their chemical composition and atomic-molecular structure. He further discusses his proposition that many students' alternative conceptions seem to be guided and constrained by common underlying tacit presuppositions (*implicit assumptions*) about the nature of entities and phenomena in our world, as well as by the application of shortcut reasoning procedures (*heuristics*) that facilitate decision-making under conditions of uncertainty (limited time and knowledge) (Talanquer 2006). The primary aim of his chapter is to illustrate how this approach can be used to analyze student reasoning about the properties of chemical substances and reactions based on atomic-molecular models of matter. Implicit assumptions and heuristics act as *constraints* on further reasoning. Paying close attention to the implicit or explicit categorization decisions made by students about the nature of chemical substance and processes can provide invaluable information about the underlying assumptions that guide their thinking.

Research on secondary school and college students' ideas about the properties of atoms and molecules indicates that many students tend to assign similar properties to the submicroscopic components of a substance as to a macroscopic sample of the material. This way of thinking relies on an "inheritance assumption," i.e., that the macroscopic properties of substances are inherited from individual submicroscopic components (Talanquer 2006, 2009). Students appear to conceptualize chemical reactions as processes driven by (a) *leading agents* (e.g., spark, match) acting upon or within a system or (b) *intentional agents* with well-defined purposes. In general, students think of chemical reactions as driven by active agents when they recognize the presence of a potential initiator or they identify some atoms or molecules as more reactive within a system (e.g., higher electronegativity, more polar). On the other hand, when the presence of a *leading* or *enabling agent* is not obvious, some states of a system are assumed to be more desirable than others. In these cases, students may consider that atoms or molecules react in order to attain a more stable final state (e.g., full valence shell, lower energy) or reinstate equilibrium. Such assumptions of *centralized causality* (active or enabling agents) or *teleology* (intentional agents) in the behavior of reacting atoms and molecules do not subside with training in the discipline. For example, in acid-base reactions hydrogen ions are transferred between molecules so that the two types of species become more stable.

Chemical substances and processes tend to be multivariate complex systems, and making proper judgments and decisions about their behavior frequently requires careful identification of and discrimination among many variables, for example, when deciding whether sodium chloride (NaCl) can be expected to have a higher melting point than sodium bromide (NaBr). Research indicates that many chemistry students do not apply an analytical way of reasoning but rather rely on heuristics to make their decisions (Maeyer and Talanquer 2010; McClary and Talanquer 2011). Heuristics tend to be domain-general reasoning strategies but also task-specific. Although heuristics usually provide satisfactory answers, they do not always lead to the correct solution and seem to be responsible for many systematic biases and errors in human reasoning. Talanquer's studies suggest that a large proportion of chemistry students rely on heuristic strategies, rather than analytical thinking based on atomic-molecular models of matter, to make ranking decisions. Talanquer considers the following to be major shortcut reasoning strategies used by chemistry students to make ranking decisions: *recognition*, *representativeness*, and *one-reason decision-making.*

Using an Anthropomorphic Conceptual Framework to Make Sense of Chemical Phenomena

Taber and Adbo (chapter "Developing Chemical Understanding in the Explanatory Vacuum: Swedish High School Students' Use of an Anthropomorphic Conceptual Framework to Make Sense of Chemical Phenomena", this volume) report on a study that was conducted in the Swedish educational context. Introductory chemistry courses in Sweden usually attempt to set up, at the beginning, a basic conceptual framework within which to situate chemical phenomena. Students learn about particle models of identifying stable ions and molecules. Many of the scientific models of the submicroscopic structure of the matter used for deriving acceptable causal explanations for chemical phenomena are not presented prior to advanced high school courses, i.e., some years after considering the phenomena that these models have been developed to explain. As a result, students may develop alternative, and sometimes idiosyncratic, imaginative notions to populate this "explanatory vacuum." The issue of how to provide adequate descriptive accounts (e.g., of chemical reactions at the submicroscopic level) without being able to offer causes for why events occur becomes a dilemma in introductory chemistry courses. One way that teachers and textbook authors resolve this issue is through the use of metaphors, anthropomorphic language, and teleological formulations. Anthropomorphism is an extension of animism and is the term used when human feelings and emotions also are assigned to nonliving things. Teleology is used to describe the special circumstance when anthropomorphism is used in explanations to provide "function and purpose" (Talanquer 2007) as being the cause of an event. Teleological and anthropomorphic formulations are very common in popular science movies and books, as well as textbooks.

In their 1-year longitudinal study, Taber and Adbo explored the level and nature of anthropomorphism used by a sample of eleven 16–18-year-old upper secondary Swedish students. Their findings indicated that there was a high level of use of anthropomorphic language in the students' explanations about basic phenomena, such as states of matter, phase change, dissolving, and reactions. In most of these contexts, with the exception of dissolving, anthropomorphism seemed to be a key feature of student explanations. Their discussion of the "behavior" of entities posited at the submicroscopic level in the theoretical models so central to modern chemistry was commonly phrased in terms of the "needs" and "wants" of atoms and molecules. Many examples occurred where students seemed to offer anthropomorphic explanations without any hint that these might be considered unsatisfactory (*strong anthropomorphism*). This is particularly the case in many of the examples of students referring to atoms "needing" to obtain full shells. However, there were also many examples where anthropomorphic explanations were offered tentatively, often with caveats that the student was not really sure what the correct explanation was.

Students' and Teachers' Models About Particle Nature: An Overview

Uncovering why and how students develop accurate, or inaccurate, ideas about the PNM is complex. As seen in the chapters on learning progressions, one cannot expect students at all educational levels to develop fully accurate scientific understanding, and, in particular, it is reasonable to expect that some degree of scientific inaccuracy attends more basic models that are aims of instruction for younger students. Children build understanding and develop private and cognitive representations of natural entities and phenomena that assist them in generating predictions and building explanations (Coll 2005; Duit 1991; Pittman 1999; Venville et al. 1994). These representations, which incorporate intuitive knowledge and commonsense reasoning, are often termed *mental models*. Mental models consist of a simplified representation of the targeted system. They are unstable, evolving, and incomplete. It is assumed that they are constructed on the spot when faced with a problem (Vosniadou 2002), but some aspects may be stored in long-term memory. The development of mental models is often also an objective of instruction, with the strategy of building mental models in the learner used for the purpose of fostering comprehension. Greca and Moreira (2000) provide a particularly clear explanation of this strategy, using the term *conceptual model* to refer to the instructional intent and *mental model* to refer to the model conjured in the student's mind: "[C]onceptual models… are logically clear and often specially designed to facilitate both comprehension and learning… [M]ental models [do not] end up as perfect copies of conceptual models, which are generated by experts and teachers, nor is the modelling process evident to our students" (Greca and Moreira 2000, p. 2).

Two major complexities accompany the measurement of mental models that students hold: (1) There is a variety of measures, and assumptions must be made about what is measured and how one measures student understanding, and (2) teachers often hold views on how and what should be taught that may not correspond to the research base on the most effective approaches toward developing students' understanding, and teachers may also hold inaccurate views of the PNM themselves. Two chapters in this volume present wide reviews of relevant research literature on the variety of students' views on the PNM (chapter "What Do We Know About Students' Beliefs? Changes in Students' Conceptions of the Particulate Nature of Matter from Pre-instruction to College", this volume) and diagnostic assessment of student understanding about the PNM (chapter "Diagnostic Assessment of Student Understanding of the Particulate Nature of Matter: Decades of Research", this volume). Five additional chapters in this part of the book present studies uncovering students' mental models and teachers' models about the PNM. These chapters include varying degrees of the intersection between teaching and learning.

What Do We Know About Students' Beliefs?

Drawing upon substantial prior conclusions in the field, Karataş et al. (chapter "What Do We Know About Students' Beliefs? Changes in Students' Conceptions of the Particulate Nature of Matter from Pre-instruction to College", this volume) argue that the PNM is a most critical "threshold concept" – a concept so basic that future understanding must be built upon it – for it plays a fundamental role in learning all sciences, and it is a portent for the future evolution of science and technology. The authors consider mental models to include beliefs and conceptions that students create, hold, and often defend. The results of a literature review of students' mental models are organized by educational level into pre-instruction, elementary-middle school, high school, and college, and a fifth category treats probes of students' views from a cross-age developmental perspective. Several trends fall out of the majority of studies: (1) a pattern of epistemic development occurs across educational levels and ages, regardless of country in which the study was conducted, "from macroscopic, continuous, non-particulate models toward particulate, atomic-molecular models," and interventions do not affect the natural epistemic development; (2) the development is slow, with a variety of rates among individuals, resulting in a distribution of PNM models present among students at each educational level, whose detection can be confounded by the ability of students to pick up accurate vocabulary (e.g., atom, molecule); (3) the development occurs in waves rather than stages, resulting in students holding different PNM models for different phenomena; and (4) preservice teachers, particularly of younger children, often demonstrate PNM views consistent with those of young students.

Karataş et al. outline a number of implications. Beyond these, we additionally point out that several of their conclusions and implications are in alignment with those on which consensus is demonstrated among other chapters in this volume. The learning progressions work reported in this volume builds upon an assumption that development is slow, and both Merritt and Krajcik, as well as Sevian and Stains, found wide distributions of PNM models present among students at the same grade levels. The conclusion of Karataş et al. that development occurs in waves is consistent with the approach advocated by Wiser et al., to focus on specific reconceptualizations across multiple phenomena. Extrapolating from the conclusions reached by Karataş et al. regarding preservice teachers' PNM views, it appears there is hope that with the validated tools of Merritt and Krajcik, it may be possible to understand much more deeply the link between teachers' PNM understanding, their instruction, and the ways in which students develop understanding of the PNM.

Diagnostic Assessment of Student Understanding of the Particulate Nature of Matter

Kahveci (chapter "Diagnostic Assessment of Student Understanding of the Particulate Nature of Matter: Decades of Research", this volume) presents a review of diagnostic assessments designed to study the understanding of particle nature concepts by students. In doing so, she provides examples of the variety of types of assessment items, and she characterizes the studies for which these assessments were designed. She finds that the purposes of the majority of studies are to describe student understanding, and that only a small number of studies investigate the effects of interventions designed to impact students' understanding of particle nature. Of the descriptive studies, the majority employ quantitative methodology. Kahveci focuses attention on two-tiered assessment as a promising tool for diagnosing students' ideas quantitatively in ways that build from qualitative research. She then provides discussion of the ways in which paradigm, methods, and methodology intersect. She also raises important questions for the design of future research studies. For example, she has demonstrated that a rich repertoire of tools now exists for diagnosing student understanding in terms of misconceptions. Thus, new research aims might be better directed toward reform-based teaching practices and their impact on student understanding.

Uncovering Students' Mental Models About Particle Nature

The Effect of an Intervention Program on Secondary School Students' Understanding of Basic Particle Nature of Matter

Treagust, Chandrasegaran, Halim, Ong, Zain, and Karpudewan (chapter "Understanding of Basic Particle Nature of Matter Concepts by Secondary School Students Following an Intervention Programme", this volume) accept that for students to be proficient in explaining the nature of matter, they need a thorough understanding of the concepts about the particle theory of matter. Therefore, it is important that students acquire a strong understanding of these particle theory concepts early on in their science studies.

Treagust et al. used the *Particle Theory Diagnostic Instrument*, *PTDI*, to diagnose and assess Grades 10 and 11 students' understanding of particle theory concepts, in a pretest/posttest design after implementing an intervention instructional program. The program involved eight lessons that included teacher demonstrations and student practical activities and was followed by class discussions to explain students' observations. The authors adopted the framework of de Vos and Verdonk (1996), about correct scientific ideas about the PNM (see chapter "Understanding of Basic Particle Nature of Matter Concepts by Secondary School Students Following an Intervention Programme", this volume, or summary provided in chapter "Introduction: Concepts of Matter – Complex to Teach and Difficult to Learn"). The instrument consists of 11 two-tier multiple-choice items which assessed understanding in three key conceptual categories: (1) intermolecular spacing in matter (CC1), (2) the influence of intermolecular forces on changes of state (CC2), and (3) diffusion in liquids and gases (CC3), using a quantitative methodology.

The *PTDI* was administered twice, once as pretest and once as posttest after an interventional instruction program. The intervention extended over eight lessons, during which the instructors demonstrated, or the students performed, experiments associated with each item of the *PTDI* where possible. Instructors then followed up with discussions about students' observations. The intervention program was found to be effective in facilitating understanding of particle concepts. In addition, nine alternative conceptions about particle concepts were found to be held by more than 10 % of students. The consistency in understanding of CC1, CC2, and CC3 was also determined, showing that students displayed very limited consistency in understanding of the associated concepts in all three conceptual categories.

The authors conclude that Grades 10 and 11 students do not have a coherent understanding of particle theory of matter concepts that were investigated in their study. It is therefore necessary that these concepts are regularly revisited from earlier school years. It is also important that teachers are familiar with the development of students' understanding about particle concepts of matter, as well as with students' misconceptions. Finally, teachers should use a variety of instructional strategies in order to expose students to a range of experiences in different contexts, as well as use of frequent and ongoing assessment.

Students' Mental Models of Gas Particles and Conceptual Change: The Application of the RAINBOW Approach

Chiu and Chung (chapter "The Use of Multiple Perspectives of Conceptual Change to Investigate Students' Mental Models of Gas Particles", this volume) present a synthesis of several studies conducted in Taiwan that use the *Research And InstructioN-Based/Oriented Work* (RAINBOW) approach (Chiu 2007, 2008; Chiu and Lin 2008) to illustrate why some conceptual understandings within the PNM are more difficult for students to learn than others. RAINBOW is a theoretical model that accounts for developmental, ontological, epistemological, affective/social, evolutionary, and instructional and modeling perspectives to explain conceptual change as students learn science. The emphasis in their chapter is on ontological and epistemological perspectives.

Chiu considers three types of ontological categories according to which concepts are assigned: *entity*, *process*, and *mental state.* Conceptual change is the process of shifting conceptions across ontological categories. Shifting from *entity* to *process* requires radical conceptual change. The *process* category has two ontologically distinct kinds of scientific processes, "direct" and "emergent." Regarding the epistemological perspective, the model adopts Vosniadou's framework theory, according to which the process of conceptual change involves a gradual lifting of the presuppositions of the framework theory and then the formation of more sophisticated models (Vosniadou et al. 2008). Presuppositions derive from everyday experience, are confirmed over years, and then are used to form a relatively coherent system of explanation (Vosniadou and Brewer 1994).

Use of the RAINBOW model is illustrated in analyzing Taiwanese middle school students' concepts of the particle nature and behavior of gases and how the effects of an instructional intervention designed to address difficult conceptual changes can be studied. In the treatment group, students were actively involved in various formats of modeling activities according to their participation in group work. For instance, in one activity students observed how different amounts of gases being pushed into a box from a hair dryer influenced the movement of plastic balls with different sizes in the box.

The findings revealed a statistically significant difference between the treatment and control group in the gained scores between the posttest and the pretest and, in particular, regarding the two main concepts, diffusion and movement. Further, the authors report the types of students' mental models of mixed gases before and after the multiple modeling activities. The authors illustrate the power of the RAINBOW approach for unpacking the conceptual changes that occurred and how particular instructional activities resulted in specific changes. In particular, they examined how students' conceptions changed from *entity* to *process*. Because many scientific concepts held by students were misplaced conceptions in "direct" and "emergent," they investigated the changes in these two kinds of processes. The theoretical background was also extended by exploiting complex system domains to provide insightful interpretations for learning gas behaviors. The authors showed that students' presuppositions of gas particles changed both ontologically and epistemologically, specifically by dramatic alterations of their mental models from synthetic to scientific models. The authors conclude that the proposed series of experiments illustrates that taking the ontological, epistemological, and modeling approaches is successful for eliciting students' deep understanding of complex systems, such as the behavior of gas particles.

The approach of Chiu and Chung relates to Wiser's ideas about reconceptualizations, in particular, that such reconceptualizations can be induced when a platform of solid research underneath is available to guide the sequencing of curriculum (see chapter "At the Beginning Was Amount of Material: A Learning Progression for Matter for Early Elementary Grades", this volume). The method of Chiu and Chung is promising in that it can be used to uncover the directions in which conceptual change begins. One can envision a scenario, based on this research, in which teachers receive formative feedback early in the process, enabling them to guide their students along productive pathways that ultimately will lead to positive conceptual changes.

Teaching with Analogies: The Atom as a Tiny Solar System

The atomic models of Thomson, Rutherford, Bohr, and quantum-mechanical theory are presented sequentially in school and in general chemistry. Research has shown that students at all levels are not comfortable with current models of the atom but prefer instead the simple abstract models, such as the Bohr model of the atom. These preliminary models are very stable and resistant to change. Nakiboğlu and Taber (chapter "The Atom as a Tiny Solar System: Turkish High School Students' Understanding of the Atom in Relation to a Common Teaching Analogy", this volume) used a diagnostic instrument designed by Taber to test 15–18-year-old Turkish students' understanding of the atomic system by means of the instructional analogy of the atom as a tiny solar system.

An analogy is a system of relations (correspondences) between parts of the structure of two domains: the *analogue domain* (also called *source* or *base domain*), which exists in memory, and the *target domain*, which contains the science concept that is the instructional objective of the analogy. The two systems may belong to different domains but share a similar structure. The analogy between the atom and the solar system is of type "between-domain," or metaphorical, analogy. This classification is based on the (perhaps often implicit) premises that (1) the atom and atomic structure are abstract, hence difficult concepts for students; (2) secondary age students are generally familiar with the general form of the solar system; and (3) there are structural similarities between the two systems. In an effort to better understand how to "make the unfamiliar familiar," the research questions and the main findings of this study were:

1. *To what extent do Turkish secondary students perceive forces acting in the atomic and solar systems to be analogous?* Students gave very similar patterns of responses in terms of how forces act in the two systems. Widespread alternative conceptions of how forces acted across both systems were detected.
2. *To what extent are alternative conceptions about the forces acting within the atomic and solar systems that have been identified among British students also found among secondary Turkish students?* Students generally recognized how the force between two bodies diminishes with distance, but other responses gave cause for concern. Most students could not accurately describe the main type of force acting in either system; and most did not appreciate the reciprocal nature of force: as acting with equal magnitude on two interacting bodies. There was evidence of a range of alternative conceptions, including the nature of equilibrium of forces. The authors find that Turkish students generally have a limited understanding of the basic physics operating in these two types of system. The students of this study often had a poor understanding of the forces acting in the solar system, suggesting that for these learners it would not be a suitable analogue to use in teaching about the planetary model of the atom. The authors listed a number of limitations of the study and suggested approaches for improvement.

By way of meta-analysis, we invoke Dagher's (1995) conviction that simply using an analogy in teaching is not as important for meaningful learning as is the way the analogy actually is used (in text, presentation, or discussion), by whom, with whom, and consequently how it is evaluated. The interaction of all these factors could provide a clearer understanding of the contribution of analogy to science learning, which is relevant to many of the chapters in this volume.

Uncovering Teachers' Models About Particle Nature

Two chapters in this volume treat the intersection between teachers' and students' mental models about the PNM. Petridou, Psillos, Hatzikraniotis, and Kallery (chapter "A Study on the Exploratory Use of Microscopic Models as Investigative Tools: The Case of Electrostatic Polarization") examine and compare the understanding of school children and preservice teachers. Their findings are consistent with the conclusion reached in the review by Karataş et al. (chapter "What Do We Know About Students' Beliefs? Changes in Students' Conceptions of the Particulate

Nature of Matter from Pre-instruction to College") that the views of preservice teachers overlap with those of the children they will teach. In this case, Petridou et al. show that there is overlap between the mental models held by students who have recently completed elementary school and those of preservice elementary school teachers. Eilks (chapter "Teacher Pathways Through the Particulate Nature of Matter in Lower Secondary School Chemistry: Continuous Switching Between Different Models or a Coherent Conceptual Structure?") introduces a novel approach to examining how veteran teachers approach teaching about the PNM – involving student teachers in interviewing teachers to seek advice on the best strategies for teaching about these ideas. In doing so, he uncovers a confusing morass of historical PNM models taught and valued by teachers, some of which are poorly understood by them.

Electrostatic Polarization as an Investigative Tool

A main aim of the National Curriculum in Greece, which is compulsory for all schools, is that students build and use "scientific models in order to describe, explain and predict some physical or chemical phenomena and processes." For Petridou et al. (chapter "A Study on the Exploratory Use of Microscopic Models as Investigative Tools: The Case of Electrostatic Polarization", this volume), the necessity of models in instruction is particularly evident when the interpretation of a phenomenon under study is not readily apparent, and submicroscopic models provide the basis for a causal account.

Electrostatic phenomena require such models. In their chapter, the authors focus on the use by students of a submicroscopic model of electrostatic polarization, by designing and implementing an educational unit. The unit focused on the active, exploratory use of a submicroscopic model as a predictive tool. Additionally, they reflected on the features of the model that would help lower secondary students and student teachers understand its use as an investigative tool. The aims of the study were to investigate: (a) whether lower secondary students and student teachers were able to use the model in order to predict the attraction between charged and uncharged balloons (phenomenon), and (b) whether the students gained awareness of the use of models as an investigative tool.

Twelve preservice primary education student teachers and 12 lower secondary students participated in a 3-h instructional unit. Both samples worked in small groups in front of a personal computer following specially developed worksheets that guided and prompted them to use the model as an investigative tool. All subjects initially were asked to predict what would happen between two balloons that were free to move, if one were negatively charged and the other uncharged, with both attached to strings hung from the ceiling close to each other. They were then introduced to the model of polarization and asked to indicate their predictions of the same phenomenon again, before the actual experiment with balloons was performed. The model of polarization consists of a sequence of three simulated representations: the atom, the dipole, and the insulator. After the experiment, students took part in a metacognitive phase that helped them become conscious of ways they utilized the model. Data were obtained by analysis of students' pre-post written predictions on the task and of tape-recorded in-depth group interviews.

The findings indicated that the features of the model that helped students to predict the phenomenon were different for different students. Student teachers seemed to have no preference for one or another of the representations of the atom, the dipole or the insulator. However, lower secondary students seemed to prefer the representation of the dipole. This preference might be due to the "direct" representation of the attractive and repulsive forces that the dipole includes, which is the cause of polarization. Regarding educational implications, the authors maintain that it is important to include the representation of both attractive and repulsive forces on dipoles in science curricula aiming at students' understanding of electrostatic polarization. In addition, teachers and curriculum designers should provide for different representations of a model in order to handle different learning prompts. The active use of models as investigative tools, combined with metacognitive procedures at the end of instruction, seemed to help students to rethink of the way they handled a model and to become conscious of the investigative power of this model.

Teacher Pathways Through the Particulate Nature of Matter

Eilks (chapter "Teacher Pathways Through the Particulate Nature of Matter in Lower Secondary School Chemistry: Continuous Switching Between Different Models or a Coherent Conceptual Structure?", this volume) reports findings from a study on research-based learning in chemistry teacher education and then continues into a project that aimed toward renovation of the German chemistry curriculum for compulsory secondary school (age 10–16). Fourth-year student chemistry teachers conducted interviews with 28 experienced chemistry teachers, with the aim of revealing German teachers' teaching strategies of the PNM, chemical reactions, and atomic structure and bonding. In accordance with the traditionally, content-oriented structure of most German curricula, three different levels were identified: (1) a level of simple discrete particles, (2) a level of atoms and atomic structure, and (3) a level of covalent bonding and molecular structure. All but one of the teachers introduced a simple model of discrete particles. Nearly all of the teachers introduced a simple particle model, in which particles are represented as hard spheres. Most teachers suggested teaching chemistry at the submicro-level based on the history of science, starting with the Dalton atomic model, moving to Rutherford, Thomson, and Bohr and followed by models of bonding (e.g., ball-and-stick), the VSEPR model, or orbital theory. Several teachers repeatedly mixed up different historical models.

By the year 2000, a group of researchers and practitioners had initiated a participatory action research (PAR) project with the aim to renovate the chemistry curriculum. The central objective was the design and development of effective teaching strategies dealing with the PNM in lower secondary chemistry teaching. The approach included development of lesson plans, cooperative learning strategies, and the integration of new media into teaching and learning. Classroom observations, teacher feedback, and group discussion allowed the researchers to form a comprehensive picture of classroom activities. From the participating teachers' viewpoint, the PNM was often insufficiently discussed by educators and by textbooks from the perspective of using different models. Some textbooks seemed to both perpetuate common misconceptions and cause even more confusion.

The PAR group worked out a new model approach for submicroscopic concepts which was internally consistent, scientifically acceptable, and compatible with students' learning capabilities. A first particle model is introduced using spheres to represent discrete particles. The spheres stand for molecules, ions (both mono- and multi-atomic), or they represent atoms in inert gases and metals. However, students at a later stage often face difficulties in distinguishing such particles from their constituent entities, that is, the single atoms that also are normally represented using spheres in the Dalton atomic model. These difficulties affect students' later understanding of chemical reactions. Finally, over a period of about 5 years, the PAR group developed an outline for a curricular framework, which (I) took into account the objective of the approach, (II) fitted into the governmental syllabus guidelines, and (III) started curriculum structuring from a thorough analysis of students' misconceptions and learning impediments. Over the last 10 years, the approach was applied to more than a hundred learning groups by the teachers in the PAR group and by teachers in in-service training courses. During this period, this strategy was operationalized through an entire curriculum published in a series of new textbooks for lower secondary chemistry classes in Germany. The teaching approach was also influential in implementing the new German science education standards in 2004, which led to new syllabi for several of the German states in their core curricula.

Educational Technology: Simulations and Visualizations

At the beginning of their chapter, Akaygun and Jones (chapter "Dynamic Visualizations: Tools for Understanding Particulate Nature of Matter", this volume) comment that 100 years ago, the PNM was a mystery even to scientists. Modern computer-generated simulations and visualizations now provide powerful images of virtual worlds that have great pedagogic value, affording beginning students opportunities to explore images of otherwise invisible molecular concepts. As Akaygun and Jones point out, there are limitations to using simulations and visualizations. For example, there is an attendant danger introduced that if care is not taken in avoiding typical pitfalls, such as artistic coloring of empty space between particles, visualizations can further cement already pervasive misconceptions, such as that particles are embedded in a continuous medium rather than in a void. This makes more important the advancement of simulations that apply a stochastic methodology, such as that described by Kalkanis (chapter "From the Scientific to the Educational: Using Monte Carlo Simulations of the Microkosmos for Science Education by Inquiry", this volume), in combination with major learnings that derive from the science education literature.

Application of the Monte Carlo Methodology for Simulating Physical Phenomena

Phenomena at the submicroscopic level, such as movements of molecules in a solid, a liquid, and a gas, are stochastic and cannot be described exactly by a deterministic algorithm. Monte Carlo statistical methodology employs computational algorithms that use sequences of random numbers to perform calculations to simulate stochastic systems. Monte Carlo methods involve complex calculations, hence are best done by a computer and have been used with great success in elementary particle research. Kalkanis (chapter "From the Scientific to the Educational: Using Monte Carlo Simulations of the Microkosmos for Science Education by Inquiry", this volume) has employed this methodology for educational applications that not only provide a realistic view of the details of complex physical systems but also are suited for studying by inquiry. The phenomena of expansion of solids, liquids, and gases and of change of state from solid to liquid and to gas when temperature rises are the focus of his chapter.

Kalkanis reports the results of studies with three groups of participants: 200 in-service teachers, 600 undergraduate primary education university students in their second and third years of study, and 300 fifth grade primary education pupils (10–11 years old) in their science class, before having been taught about the relevant phenomena. All participants spent 4 h on selected units performing (in groups of three) experiments concerning expansion and compression of materials and changes of state, watching and interacting with the relevant educational software, completing worksheets, and recording their observations.

Participants answered written questionnaires before and after the intervention. The questionnaires included questions about how participants would explain macroscopic properties (volume, shape, and rigidity or viscosity) of the materials based on the positions and micro-movements of their particles/molecules; expansion or compression of solids, liquids, and gases; and change of state. The findings indicated that both teachers and university students understood the particulate structure of matter, connected submicroscopic processes with macroscopic phenomena, and felt confident that they could use the model to explain macroscopic phenomena to their pupils. The pupils understood the PNM less well but made efforts to connect submicroscopic processes with macroscopic phenomena, providing in some cases explanations where macroscopic properties and submicroscopic processes were confused.

A Review of Studies on Visualizations and Simulations as Tools for Understanding the Particulate Nature of Matter

According to Jones and colleagues, visualization and modeling tools have the potential to make a profound difference in how molecular-level concepts are learned and understood (Jones et al. 2005). Akaygun and Jones (chapter "Dynamic Visualizations: Tools for Understanding the Particulate Nature of Matter", this volume) review some of the research studies that have attempted to identify the effects of dynamic visualizations on learning, and discuss design principles for the development of effective visualizations and their implications both for developers and for instructors. The review includes studies on animations and still images, on simulations, and on combinations of dynamic visualizations with macroscopic observations. It also examines effects of gender differences.

Research verifies that models and images of molecular structure and interactions on paper or chalkboard, commonly used in the teaching of chemistry, have educational value, especially when combined with activities in which students design their own representations. Visualizations are more easily interpreted by learners when physical models or computer models are used. On the other hand, phenomena that involve motion and chemical processes can be better represented by animations. A number of dynamic visualizations have been designed to include both macroscopic and submicroscopic representations to teach fundamental concepts of chemistry. Animations of the particulate level of matter can help students better to visualize the PNM, enhance conceptual understanding, and overcome misconceptions. Animations have also been incorporated into hypermedia environments, combining multimedia and hypertext in order to enhance conceptual understanding at the submicroscopic level.

Some research has examined effects of individual differences. Students who viewed animations scored higher on tests of conceptual understanding than students who viewed still images. No interaction with spatial ability was detected. However, in a test of the ability of students to transfer their knowledge, no differential effect of viewing the animation was seen. On the other hand, viewing animations led to higher average scores only for students in the high spatial ability group, while students with low spatial ability may have more difficulty transferring knowledge gained from viewing animations. The effect of gender on the ability of students to learn from submicroscopic level animations has also been investigated. Animations helped both male and female students to improve their scores, but the gain in score for female students was significantly greater than for male students.

Computer simulations have been developed and used in a variety of chemistry courses and laboratory applications for different levels of students. Early applications of simulations were directed toward general chemistry laboratories and most simulated macroscopic laboratory procedures. Animations and simulations can certainly be useful tools in the chemistry classroom. However, they have limitations, so care must be taken in their selection and usage. A limitation of animations is that they are just simple representations of the submicroscopic level and cannot be perfectly accurate, so students may develop simplistic or incomplete understanding of the submicroscopic level. On the other hand, not all studies of animations and simulations have revealed positive effects. Cognitive theories of multimedia learning suggest that when students are required to pay attention to several tasks simultaneously, a portion of the working memory may not be available for learning (Mayer 1997). Having different types of representations in visualizations may cause learners to experience difficulties in processing this information.

Chemical Structure and Bonding

The study of chemical reactions and syntheses lies at the heart of chemistry. Reactions involve the breaking and forming of chemical bonds. Chemical structure and bonding apply to all chemical and biochemical systems and consequently are key concepts in chemistry. Additionally, knowledge of structure and bonding are used in predictions of physical and chemical properties of compounds (structure-property relationships).

Lewis' concept of valency was revolutionary in chemistry and is still useful today. Lewis structures differentiate between polar and nonpolar molecules. Remarkably, Lewis devised the theory many years before the development of quantum-mechanical calculations on molecules (Lewis 1916), and it has survived these developments. By analyzing wave functions or electron densities, quantum chemists have obtained similar structures to this for many types of molecules. For example, quantum-chemical calculations show (Suidan et al. 1995), in a number of common ions and molecules (e.g., sulfate, perchlorate, and phosphate ions, sulfur trioxide, and sulfur dioxide), that the original Lewis structures, which generally abide the octet rule, represent these species *more accurately* than the leading resonance structures cited in freshman chemistry textbooks. Lewis' theory does not cover all molecular structure, so modifications have been introduced to make it consistent with the results for molecules containing polar covalent bonds (e.g., ClF) and hypervalent atoms (e.g., SF_6) and for coordinate and nonintegral bonds (Nelson 2001a, b).

Another powerful and very popular model of molecular structure is *valence shell electron pair repulsion*, or VSEPR (see Gillespie 1963). The model is related to electron density. It is important to take into account that the fundamental basis for the VSEPR model is provided by the Pauli exclusion principle and not by electrostatics: electrons exhibit their behavior as a consequence of the Pauli exclusion principle of same-spin electrons, and not primarily as a consequence of their electrostatic repulsion. Regarding the atomic structure, electron pair repulsion dictates that free atoms or monatomic ions with an octet of electrons in their valence shells (such as Ne, F^-, O^{2-}) *do not* have four electron *pairs* (as commonly depicted), but instead electrons move freely around the corresponding nucleus, giving a spherical total electron density (Gillespie and Matta 2001). In quantum-chemical terms, this is a result of *electron correlation* (Levine 1991; Pilar 1968; Tsaparlis 2001).

The construction of a Lewis structure for a simple molecule, combined with the VSEPR model, leads to the determination of the shape of the molecule. Following that, the electronegativity model of Pauling can guide the determination of the direction of polarity of each bond, and then the combination of the bond polarity for each bond leads to the determination of overall molecular polarity of small molecules or regions (e.g., functional groups) of large molecules. The combination of the three-dimensional structure and electron density distribution determines the nature of intermolecular bonding, which can be used in prediction of physical and chemical properties of the compound (i.e., relative melting or boiling points, acidity, and basicity) (Cooper et al. 2012).

Finally, in quantum-chemical terms, chemical bonding is associated on the one hand with the molecular orbital model initiated and developed, among others, by Hund, Mulliken, and Coulson (c.f., Coulson 1952), and on the other hand by the valence bond model advocated first by Lewis and later developed by Pauling. Although these two approaches appear to be antagonistic, with increasing approximation they converge to a common model. Pauling claimed that what he was doing was, in effect, the theoretical justification of what Lewis had already suggested so successfully nearly 20 years earlier: an explanation for the otherwise mysterious electron pair mechanism (Gavroglu and Simões 2012).

The collection of chapters ("Teaching and Learning of the Chemical Bonding Concept: Problems and Some Pedagogical Issues and Recommendations", "A Common Core to Chemical Conceptions: Learners' Conceptions of Chemical Stability, Change and Bonding", "Macro–Micro Thinking with Structure–Property Relations: Integrating 'Meso-levels' in Secondary Education" and "Learning and Teaching the Basic Quantum Chemical Concepts") in this section of the book provides insight into the difficulties students experience in confronting these models and approaches to instruction that can ameliorate some of these challenges. Taber (chapter "A Common Core to Chemical Conceptions: Learners' Conceptions of Chemical Stability, Change and Bonding", this volume) reviews a number of his own, as well as other, relevant studies on how students understand bonding. Levy Nahum, Mamlok-Naaman, and Hofstein (chapter "Teaching and Learning of the Chemical Bonding Concept: Problems and Some Pedagogical Issues and Recommendations", this volume) offer a self-consistent principled approach to teaching bonding. Meijer, Bulte, and Pilot (chapter "Macro–Micro Thinking with Structure–Property Relations: Integrating 'Meso-levels' in Secondary Education", this volume) illuminate a deeper challenge – that there are actually multiple structural dimensions in which bonding is relevant. Finally, Tsaparlis (chapter "Learning and Teaching the Basic Quantum Chemical Concepts", this volume) reviews challenges with teaching and learning quantum chemistry models.

A Common Alternative Explanatory Principle for the Concepts of Chemical Stability, Change, and Bonding

Taber (chapter "A Common Core to Chemical Conceptions: Learners' Conceptions of Chemical Stability, Change and Bonding", this volume) reviews studies of his that have led to a *common core to chemical conceptions* on chemical stability, change, and bonding. Taber (1998) claimed that among students entering the college chemistry courses, "there was an adoption of a common explanatory principle, that chemical processes can be explained at the submicroscopic level in terms of atoms acting to acquire particular electronic configurations…students would refer to atoms *filling their shells* or obtaining *octets* of outer electrons, or acquiring *noble gas electronic configurations.*" Certain electronic arrangements were assumed to have inherent stability (a reasonable interpretation), leading students to see the ability to acquire these arrangements as sufficient basis for explaining chemical processes (an inappropriate generalization). Students believe that shared electrons form a covalent bond, as it allows the shared electrons to be counted in the valence shells of both of the atoms and so allows these atoms to be said to have full shells. This is considered both the reason for the bond forming and for why it acts as a bond. Students employ anthropomorphism and teleology, by referring to atoms as *wanting* or *needing* to fill their shells and forming bonds so that they may do so.

In the case of ionic bonding, for most students, the most salient idea was that of an electron transfer between atoms. An alternative "molecular" framework for ionic bonding has been adopted by many students, with four common features: (a) the presence of molecules or molecule-like entities, (b) the history conjecture (an ionic bond only exists between ions that have experienced an electron transfer event together), (c) the valency conjecture (an atom can only form as many ionic bonds as the number of electrons it is able to donate or accept in forming an ion with a full outer shell), and (d) the "just forces" conjecture (there are two types of interactions in the ionic lattice, ionic bonds, where electron transfer has occurred, and just forces between adjacent ions that are not bonded through having experienced electron transfer).

In college level chemistry, students are taught that covalent and ionic bonds are, in effect, models of ideal cases, and that most bonding in compounds is best understood as intermediate between covalent and ionic bonding. The metallic or nonmetallic nature of elements is not taught as a dichotomy, but in terms of the electronegativity scale, and it follows that ionic-covalent represents a continuum, with bonds found at different points along the dimension. There is the tendency to see polar bonds as distorted covalent bonds, which reflects the full-shells explanatory principle as the common starting point for thinking about bonding. When thinking in terms of an electrical model (as presented in the college curriculum), the bond can be considered as an electron pair found between two atomic cores, which may be completely located on one atom (ionic), evenly shared between the two atoms (covalent) or, more often, somewhere in between (polar). However, the notion of polar bonding does not readily follow from the full-shells explanatory principle, so for students who consider an atom's needs to fill its shells as the driving force for chemical processes, teaching about bond polarity is *interpreted* as a secondary electrical perturbation, superimposed on the basic template of a covalent bond.

Other interactions such as those allowing solvation to occur, or van der Waals forces, are also very important in chemistry, but are not considered to be types of chemical bonds by students. Students tend to make a sharp distinction between what they see as proper chemical bonds that can be explained in terms of the full-shells explanatory principle and other effects which are "just forces." Hydrogen bonding features as an important type of interaction in advanced chemistry courses, with a significant role in the structure of proteins and nucleic acids. Hydrogen bonds cannot be explained in terms of the full-shells explanatory principle, as the atoms involved are already formally bonded. An approach to teaching bonding that may circumvent many of these difficulties is offered in chapter "Teaching and Learning of the Chemical Bonding Concept: Problems and Some Pedagogical Issues and Recommendations".

A Bottom-Up Approach to Teaching Bonding

Levy Nahum, Momlok-Naaman, and Hofstein (chapter "Teaching and Learning of the Chemical Bonding Concept: Problems and Some Pedagogical Issues and Recommendations", this volume) are concerned about the effect that external resources, such as textbooks, exercise on teaching and learning. They invoke Stinner (1995) and Sutton (1996) to comment that "textbooks tend to present science as a collection of true or complete facts and as generalizations and mathematical formulations, as if the material has been 'read directly from nature'." The way textbooks and teachers present the classification of chemical bonds, as if everything is very simple and clear, is deluding and misleading (Yifrach 1999).

The authors consider several reasons for dissatisfaction with the current teaching and learning of the bonding concept: (1) the traditional *pedagogical approach*, as it appears mainly in many chemistry textbooks worldwide, and (2) the *assessment* methods used worldwide (high-stakes testing). In Israel, for instance, examinations influence teachers' instruction and students' learning regarding the *bonding* concept, because teachers' main objective becomes to prepare students for a matriculation examination, often leading to superficial teaching that results in misconceptions and pseudo-conceptions (Levy Nahum et al. 2004, 2007).

In an attempt to overcome some of the conceptual problems about the chemical bond concept, these authors, as part of an effort at the Weizmann Institute of Science, carried out a longitudinal project in Israel, in which the main goals were to diagnose the sources and nature of relevant student learning difficulties and misconceptions and to develop a model for learning and instruction to overcome these. In their project they were guided by Gillespie's (1997) suggestions about the treatment of chemical bonding in introductory general chemistry courses: that all chemical bonds are formed by *electrostatic attractions* between positively charged cores and negatively charged valence electrons. The project consisted of three sequential phases. The first phase was diagnostic, aiming at spotting the causes of difficulties and misconceptions. The second phase involved the development of a model for teaching the chemical bonding concept. In the third phase (implementation), the new teaching model was implemented in one high school (as a case study). The development of the new teaching approach for the bonding concept was based on the construction of a reformed approach aligned with scientists' views. The authors employed the expertise of chemistry teachers, scientists, and chemistry educators, as well as several methods of developmental activities such as a scientific symposium, a focus group, and in-depth interviews.

The general approach relies on basic concepts and ideas, such as Coulomb forces and energy at the atomic level, to build a coherent and consistent perspective for dealing with all types of chemical bonds. This *bottom-up approach* to teaching bonding starts from the elemental principles of an isolated atom (stage 1), then discusses the general principles of bonding between two atoms (stage 2), and finally uses these general principles to the traditional categories of chemical bonding as extreme cases of various continuum scales (stage 3). Equipped with this knowledge, students can then construct a coherent understanding of different molecular structures (stage 4) and properties (stage 5).

Such an approach provides a basic theoretical foundation that may support later reconceptualizations (chapter "At the Beginning Was Amount of Material: A Learning Progression for Matter for Early Elementary Grades", this volume). However, systems of interest in modern chemistry and modern materials science are very complex. The work described in chapter "Macro–Micro Thinking with Structure–Property Relations: Integrating 'Meso-levels' in Secondary Education" illuminates new challenges to learning that emerge from this complexity and introduces an approach to considering learning that may help students navigate these challenges.

The Role of "Meso-Levels" in Structure-Property Relations

Meijer, Bulte, and Pilot (chapter "Macro–Micro Thinking with Structure–Property Relations: Integrating 'Meso-levels' in Secondary Education", this volume) consider the connection of macro-(sub)microthinking with structure-property relations and suggest integrating the so-called meso-levels in secondary education. Meso-levels link macroscopic phenomena characterized by observable/measurable properties to submicroscopic models to facilitate a thinking process using structure, properties, and their interrelations at the different levels. A "structure-property relation" is a causal relation between a structure at meso- or submicro-level and a property. Structure-property relations usually have a qualitative character (causal relations in words) and can be expressed as if-then clauses.

Materials are built up from smaller structural elements, which themselves are built from yet smaller-scale structural elements (Aguilera 2006). Material structures are interpreted as systems and subsystems with properties. Subsystems become manifest when studying structures and properties of macroscopic objects and materials. Different subsystems can be distinguished from one another based on differences in structures and properties. Structure-property relations are the specific relations between the substructures in the corresponding subsystem and the emergent property. The property of the structure can be explained by interactions between substructures (Rappoport and Ashkenazi 2008). An example presented in the chapter is bread based on wheat. Bread can be defined as a final fixed form of dough. When scientists repeatedly "zoom deeper" into dough, by using light or electron microscopes, they are able to distinguish certain structures, such as walls of gas holes, threads, granules imbedded in networks, and entwined long molecules (Meijer 2011; Meijer et al. 2009). These structures are examples of intermediate meso-structures at scales between 10^{-1} and 10^{-7} m, which are related to properties such as the elasticity of walls of gas holes, the strength of a thread, the flexibility of textile, and the stiffness of cloth. The authors illustrate linking structures to properties with three examples from three different domains of chemistry: (1) the elongation of wheat bread (biochemistry), (2) stiff and strong bike wheels made of poly-p-phenylenebenzo-bisoxazole (polymer chemistry), and (3) the stable character of benzene (organic chemistry). The first two examples were chosen to illustrate the necessary use of meso-structures for relating structures to properties, while the third example shows a limiting case with properties at the macro-level directly related to structures at a molecular level.

The authors propose a strategy for using this macro-(sub)microthinking in high school. The strategy consists of the following steps: (1) conceive a material as a system of subsystems at the meso- and microlevel, (2) use intuitive notions that a property can be explained/predicted by structures within the material, (3) use intuitive notions about "structure" and "property," (4) use explicit scaling of structures, (5) use explicit terminology in modeling and use metaphors, (6) use subsequent analogous examples, and (7) use interdisciplinary examples. Finally, employing the above strategy for design, the authors introduced two new curriculum units in a new context-based upper secondary education program in the Netherlands. The outcomes of this research project were used and further elaborated using the teachers' experiences. In the chapter, the authors describe examples from the units and illustrate the approach through these.

Learning and Teaching the Basic Quantum-Chemical Concepts

Both Levy Nahum et al. (chapter "Teaching and Learning of the Chemical Bonding Concept: Problems and Some Pedagogical Issues and Recommendations", this volume) and Meijer et al. (chapter "Macro–Micro Thinking with Structure–Property Relations: Integrating 'Meso-levels' in Secondary Education", this volume) above focus on models of chemical bonding that relate to classical physics and/or old quantum theory. Quantum chemistry attempts to explain chemical bonding by describing atomic and molecular systems by means of mathematical functions and expressions that derive from Schrödinger's wave mechanics. Indeed, the quantum-chemical concepts "have their origin in the bringing together of mathematics and chemistry" (Coulson 1974, p. 17). Today, it is generally acceptable that quantum mechanics has brought a new way of looking at the world of atoms and molecules. However, the view that chemistry has been or can be reduced to physics, specifically to quantum mechanics, is considered mistaken (Scerri 2001). Indeed, the way chemists see and use quantum mechanics is entirely different from that of physicists. Chemists are comfortable with using orbitals and orbital ideals, but even many practicing chemistry researchers have adopted a quasi-quantum character to the quantum chemistry tools they employ, seeing chemistry as autonomous from physics (Sánchez Gómez and Martín 2003). In their recent book about the history of quantum chemistry, Gavroglu and Simões (2012) propose that the root of this resistance of chemists to include mathematics and physics to understand quantum chemistry refers to Pauling, Lewis, and Coulson. For example, Pauling stressed the use of quantum mechanics in order to understand the chemical bond but at the same time kept mathematical formalism to a minimum, appealing to "chemists' intuition" and experimental data. Coulson pointed out that the major contribution of quantum mechanics was not to have provided its mathematical theory but rather facilitated insight and understanding at a deeper level. In his chapter (chapter "Learning and Teaching the Basic Quantum Chemical Concepts", this volume), Tsaparlis reviews research on challenges to teaching and learning basic quantum-chemical concepts.

Basic quantum-chemical models and concepts, such as atomic orbitals (AOs), molecular orbitals (MOs), and hybridization, are now a part of undergraduate general chemistry and introductory inorganic and organic chemistry courses. They are also standard components of most senior high school curricula at advanced or special levels. Tsaparlis first overviews the related educational literature and then reviews his own research group's studies on misconceptions and learning difficulties occurring with students at the high school and at the university level. These studies examined students' views on abstract quantum concepts, with emphasis on the ideas they expressed about the theoretical descriptions of nonobservable entities and the connections they made between nonobservables and reality. The studies included analyzing examination papers, written answers to questionnaires, and interviews with students.

Twelfth grade students performed differently in conceptual questions that differed from the standard simple recall or application/algorithmic questions set in the examinations. The algorithmic behavior does not presuppose conceptual understanding and vice versa. Performance dropped, usually dramatically, when dealing with conceptual questions. The findings point at three main problems in the learning of the basic quantum-chemical concepts by high school and freshmen university students: (a) the insistence on the deterministic models of the atom derived from old quantum theory; (b) the misinterpretation of models and theories, and the poor understanding of the modern quantum concepts, including their mathematical features; and (c) the formation of misunderstandings and misconceptions. Further, using the method of phenomenography, beginning undergraduate chemistry students' explanations and models of a number of quantum chemistry concepts were examined. Applying Ausubel's theory of meaningful learning (c.f. Ausubel 2000), the explanations and models were placed in the meaningful learning/rote learning continuum. Finally, an interview study with first-year students at the start of their courses (i.e., their knowledge was deriving from high school), aimed to change students' ideas into modern (probabilistic, quantum-mechanical) views. The methodology proved useful for all students, irrespective of their performance on traditional written exams.

Structure in Organic Chemistry and Biochemistry

No doubt, structure plays a fundamental role in organic chemistry and in biochemistry, but unfortunately this volume did not include relevant chapters. To fill these holes, we will attempt a brief and, of necessity, incomplete reference to places where structure presents a main challenge to learning in these areas of chemistry.

Organic Chemistry

Various methods of representing structural formulas of organic compounds are introduced early in the study of organic chemistry. Students are taught to identify and differentiate among constitutional and geometric isomers, conformers, and stereoisomers. More complicated spatial tasks include the study of stereoselective mechanisms and relationships among structure, reactivity, and kinetics. Spatial perception and reasoning is assumed to be a determining factor in the overall study of organic chemistry. Individual differences in spatial ability may or may not predict success on spatial problems in organic chemistry. Harle and Towns (2011) reviewed the spatial ability literature, its connections to chemistry, and implications for instruction. Stieff et al. (2012) investigated the strategies used by students to solve spatial chemistry problems, and the relationships between strategy choice, spatial ability, and gender, and reported that students employ multiple strategies, such as algorithms and heuristics, and the construction of external diagrams, rather than relying exclusively on image-based reasoning. Students' choice of strategy was found to be independent of visual-spatial ability, while female students employed strategies different than male ones after relevant instruction.

Reaction Mechanisms and Curved Arrows

A central and widespread practice for teaching reaction mechanisms is to use Lewis structures and curved arrows to denote the motion of electrons. Electron transfer (from bonding to antibonding orbitals) effects, such as delocalization and hyperconjugation, can be translated into a language referring to resonance structures of covalent and ionic components of bonds (Karafiloglou 2002).

While reaction mechanisms and the tool of curved arrows have been criticized as a universal explanatory device (Laszlo 2002), they are a very useful and integral component of most organic chemistry courses. Little research has been conducted on the difficulties students experience with understanding the meaning associated with curved arrows during a single moment in time (Bhattacharyya and Bodner 2005; Ferguson and Bodner 2008). Grove et al. (2012b) used OrganicPad, a computer-based structure drawing program, to explore how second-year organic chemistry students changed their study of the subject over time and reported a dramatic evolution of mechanistic strategies during the academic year. Building on these findings, Grove et al. (2012a) found that students who engaged in the use of mechanisms were better equipped to solve organic chemistry problems but only those that involve transfer of knowledge.

Biochemistry

Biological Molecules and Biological Function

Contributions of molecular sciences to the development of biochemistry and molecular biology are foundational. A central idea is biomolecular structure as related to biological function. However, the structural nature of biological molecules presents new demands on conceptual understanding. For instance, understanding the three-dimensional nature of structures of proteins is essential if students are to understand how proteins fold into thermodynamically favorable conformations and form biologically relevant complexes (Canning and Cox 2001). According to these authors, molecular models are much less effective in biochemistry, compared to organic chemistry, because it takes many atoms to demonstrate structural motifs. They argue that a better and more versatile way to view the three-dimensional structure of biological molecules is through the use of molecular visualization software.

The conceptual content of these virtual representations is frequently very high: understanding the interaction between the visual image and conceptual knowledge it conveys is at the heart of chemistry and biochemistry. Constructing deeper understanding through multiple representations is divided into three subfunctions of *abstraction*, *extension*, and *relation* (Ainsworth 1999). Of relevance here is abstraction, which pertains to seeing the invariance and distinctions across representations. In the domain of biochemistry, this should be akin to developing an understanding of the affordances and constraints of the various representations of protein molecules such as ribbon diagrams, wireframe vies, or hydrophobic/hydrophilic surfaces.

According to Towns et al. (2012), visual literacy (the ability to interpret and create external representations) is essential to success in biochemistry. The Taxonomy of Biochemistry External Representations (TOBER) was proposed by Towns and co-workers as a method for classifying the types of external representations used in biochemistry classrooms. To this end, the authors extended Johnstone's well-known triangle of the domains of chemical knowledge by adding the discipline of biochemistry and thus forming the "biochemistry tetrahedron." TOBER is mapped onto it.

Closing Words

In closing, we return to words in the Foreword by Peter Fensham: "The emergence of another very substantial book covering a further number of approaches to both the research and teaching about 'matter' is both a source of encouragement and despair. I am encouraged by the positive note that underpins the innovative nature and novelty of the approaches now being reported. I despair that such abstract macroscopic and microscopic notions in science are still largely being directly transmitted as definitions in science education, rather than emerging as the culmination of experiencing many of the relevant natural phenomena, including ones that involve those exciting new forms of matter that are not yet even on the horizon of our school science agenda." Fensham rightly points out that there are many concepts of matter that the book does not deal with, such as colloids, plasma, glass, nucleons, and elementary particles (the latter including the Higgs boson).

Concepts of matter are complex, difficult to teach and difficult to learn. Doing so well is critical in understanding and operating daily in the world around us, but there is a more important purpose. Modern materials have transformed how we live, increased the quality of human life, and are at the foundation of today's economies. But they have also opened a Pandora's Box of environmental, societal, and economic problems. The future of human life on this planet depends on intelligent, responsible, and deliberate action by current and future generations of people who well understand and depend on concepts of matter. It begins with education. It is our hope that this book advances us toward this end. Let us hope that the next book covering concepts of matter, a decade or so hence, will see our societies, educational systems, and approaches to education having moved further toward a state in which students emerge more prepared to engage in this calling. Furthermore, the particulate nature of matter, while possessing critically important explanatory power, is but one of a small set of core ideas in science. For example, the chemical enterprise is about the design of chemicals, to which the particle nature of matter is at service, and includes such core ideas as chemical mechanism and control of processes, as well as benefits and costs in chemical design that take into consideration chemical fate and transport with societal, political, environmental, economic, and individual concerns. Let us, therefore, hope also that future books concerning the teaching and learning of concepts of matter address the broader ideas that the explanatory power of the particle nature of matter serves.

Then he spoke and the sea was born
And I saw and marveled
And in it he sowed small worlds in my image
and likeness
………………………………….
and broad the sky above
that you may read the infinite yourself
THIS
the world the small, the great!*

"AND THIS THE WORLD you must see and receive"

(The AXION ESTI, Genesis, 1959;
by Odysseas Elytis: 1911–1996, Nobel Prize in Literature, 1979)

* ΑΥΤΟΣ Ο ΚΟΣΜΟΣ Ο ΜΙΚΡΟΣ, Ο ΜΕΓΑΣ!
(Af'tos o 'kosmos, o mi'krós, o 'megas!)

References

Aguilera, J. M. (2006). Food product engineering: Building the right structures. *Journal of the Science of Food and Agriculture, 86*, 1147–1155.

Ainsworth, S. E. (1999). A functional taxonomy of multiple representations. *Computers in Education, 33*, 131–152.

Ausubel, D. P. (2000). *The acquisition and retention of knowledge: A cognitive view*. Dordrecht: Kluwer Academic Publishers.

Basolo, F. (1984). Teaching of chemical reactions and syntheses. *Journal of Chemical Education, 61*, 520–521.

Bhattacharyya, G., & Bodner, G. (2005). It gets me to the product. How students propose reaction mechanisms. *Journal of Chemical Education, 82*, 1402–1407.

Canning, D. R., & Cox, J. R. (2001). Teaching the structural nature of biological molecules: Molecular visualization in the classroom and in the hands of students. *Chemistry Education Research and Practice, 2*, 109–122.

Chalmers, A. F. (2009). *The scientist's atom and the philosopher's stone: How science succeeded and philosophy failed to gain knowledge of atoms* (Boston studies in the philosophy of science, Vol. 279). Dordrecht/Heidelberg/London/New York: Springer.

Chiu, M. H. (2007). *Research and InstructioN-Based/Oriented Work (RAINBOW) for conceptual change in science learning.* Paper presented at the 2nd Network for Inter-Asian Chemistry Educators Symposium, Taipei.

Chiu, M. H. (2008, March 29–April 2). *Research And Instruction-Based/Oriented Work (RAINBOW) for conceptual change in science learning – An example of students' understanding of gas particles*. Paper presented at the NARST 2008, Baltimore.

Chiu, M. H., & Lin, J. W. (2008). Research on learning and teaching of students' conceptions in science. In I. V. Eriksson (Ed.), *Science education in the 21st century* (pp. 291–316). New York: Nova Science Publishers, Inc.

Coll, R. K. (2005). The role of models, mental models and analogies in chemistry teaching. In P. J. Aubusson, A. G. Harrison, & S. M. Ritchie (Eds.), *Metaphor and analogy in science education* (pp. 65–77). Dordrecht: Springer.

Cooper, M. M., Underwood, S. M., & Hilley, C. Z. (2012). Development and validation of the implicit information from Lewis structures instrument (IILSI): do students connect structures with properties? *Chemistry Education Research and Practice, 13*, 195–200.

Coulson, C. A. (1952). *Valence*. Oxford: Clarendon Press.

Coulson, C. A. (1974). Mathematics in modern chemistry. *Chemistry in Britain, 10*, 16–18.

Dagher, Z. R. (1995). Review of studies on the effectiveness of instructional analogies in science education. *Science Education, 79*, 295–312.

de Vos, W., & Verdonk, A. H. (1996). The particulate nature of matter in science education and in science. *Journal of Research in Science Teaching, 33*, 557–664.

Duit, R. (1991). On the role of analogies and metaphors in learning science. *Science Education, 75*, 649–672.

Duschl, R., Maeng, S., & Sezen, A. (2011). Learning progressions and teaching sequences: A review and analysis. *Studies in Science Education, 47*(2), 123–182.

Ferguson, R., & Bodner, G. (2008). Making sense of the arrow-pushing formalism among chemistry majors enrolled in organic chemistry. *Chemistry Education Research and Practice, 9*, 102–113.

Gavroglu, K., & Simões, A. (2012). *Neither physics nor chemistry: A history of quantum chemistry*. Cambridge, MA: Massachusetts Institute of Technology Press.

Gillespie, R. J. (1963). The valence-shell electron-pair repulsion theory of directed valency. *Journal of Chemical Education, 40*, 295–301.

Gillespie, R. (1997). The great ideas of chemistry. *Journal of Chemical Education, 74*, 862–864.

Gillespie, R., & Matta, C. F. (2001). Teaching the VSEPR model and electron densities. *Chemistry Education Research and Practice, 2*, 73–90.

Greca, I. M., & Moreira, M. A. (2000). Mental models, conceptual models, and modelling. *International Journal of Science Education, 22*, 1–11.

Grove, N. P., Cooper, M. M., & Cox, E. L. (2012a). Does mechanistic thinking improve student success in organic chemistry? *Journal of Chemical Education, 89*, 850–853.

Grove, N. P., Cooper, M. M., & Rush, K. M. (2012b). Decorating with arrows: Toward the development of representational competence in organic chemistry. *Journal of Chemical Education, 89*, 844–849.

Harle, M., & Towns, M. (2011). A review of spatial ability literature, its connection to chemistry, and implications for instruction. *Journal of Chemical Education, 88*, 351–360.

Hasper, P. S. (2006). Aristotle's diagnosis of atomism. *Apeiron: A Journal for Ancient Philosophy and Science, 39*(2), 121–155.

Johnson, P. (1998). Progression in children's understanding of a "basic" particle theory: A longitudinal study. *International Journal of Science Education, 20*, 393–412.

Johnson, P. M. (2002). Children's understanding of substances, part 2: Explaining chemical change. *International Journal of Science Education, 24*, 1037–1054.

Johnson, P. (2005). The development of children's concept of a substance: A longitudinal study of interaction between curriculum and learning. *Research in Science Education, 35*, 41–61.

Johnson, P., & Tymms, P. (2011). The emergence of a learning progression in middle school chemistry. *Journal of Research in Science Teaching, 48*, 849–877.

Jones, L. L., Stillings, N. A., & Jordan, K. D. (2005). Molecular visualization in chemistry education: The role of multidisciplinary collaboration. *Chemistry Education Research and Practice, 6*, 136–149.

Karafiloglou, P. (2002). Understanding delocalization and hyperconjugation in terms of (covalent and ionic) resonance structures. *Chemistry Education Research and Practice, 3*, 119–127.

Laszlo, P. (2002). Describing reactivity with structural formulas, or when push comes to shove. *Chemistry Education Research and Practice, 3*, 113–118.

Levine, I. N. (1991). *Quantum chemistry* (5th ed.). Upper Saddle River: Prentice-Hall.

Levy Nahum, T., Hofstein, A., Mamlok-Naaman, R., & Bar-Dov, Z. (2004). Can final examinations amplify students' misconceptions in chemistry? *Chemistry Education Research and Practice, 5*, 301–325.

Levy Nahum, T., Mamlok-Naaman, R., Hofstein, A., & Krajcik, J. (2007). Developing a new teaching approach for the chemical bonding concept aligned with current scientific and pedagogical knowledge. *Science Education, 91*, 579–603.

Lewis, G. N. (1916). The atom and the molecule. *Journal of the American Chemical Society, 38*, 762–785.

Maeyer, J., & Talanquer, V. (2010). The role of intuitive heuristics in students' thinking: Ranking chemical substances. *Science Education, 94*, 963–984.

Mayer, R. E. (1997). Multimedia learning: Are we asking the right questions? *Educational Psychologist, 32*, 1–19.

McClary, L., & Talanquer, V. (2011). Heuristic reasoning in chemistry: Making decisions about acid strength. *International Journal of Science Education, 33*, 1433–1454.

Meijer, M. R. (2011). *Macro-meso-micro thinking with structure-property relations for chemistry education – An explorative design-based study.* Ph.D. thesis, Freudenthal Institute for Science and Mathematics Education, Faculty of Science, Utrecht University, FIsme Scientific Library (formerly published as CD-β Scientific Library), Utrecht, nr 65.

Meijer, M. R., Bulte, A. M. W., & Pilot, A. (2009). Structure-property relations between macro and sub micro representations: Relevant meso levels in authentic tasks. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education* (Model and modeling in chemical education, Vol. 4, pp. 195–213). Dordrecht: Springer.

Merritt, J., Schwartz, Y., Sutherland, L. M., & Krajcik, J. (2012). How can I smell things from a distance? In J. S. Krajcik, B. J. Reiser, L. M. Sutherland, & D. Fortus (Eds.), *Investigating and questioning our world through science and technology (IQWST)*. New York: Sangari Global Education.

Mohan, L., Chen, J., & Anderson, C. W. (2009). Developing a multi-year learning progression for carbon cycling in socio-ecological systems. *Journal of Research in Science Teaching, 46*, 675–698.
Nelson, P. G. (2001a). Modified Lewis theory, part 1. Polar covalent bonds and hypervalency. *Chemistry Education Research and Practice, 2*, 67–72.
Nelson, P. G. (2001b). Modified Lewis theory, part 2. Coordinate and nonintegral bonds. *Chemistry Education Research and Practice, 2*, 179–182.
Nelson, P. G. (2003). Basic chemical concepts. *Chemistry Education Research and Practice, 4*, 19–24.
Niaz, M., & Rodriguez, M. (2000). Teaching chemistry as rhetoric of conclusions or heuristic principles – A history and philosophy of science perspective. *Chemistry Education Research and Practice, 1*, 315–322.
Nussbaum, J. (1998). History and philosophy of science and the preparation for constructivist teaching: The case of particle theory. In J. J. Mintzes, J. H. Wandersee, & J. D. Novak (Eds.), *Teaching science for understanding – A human constructivist view*. London: Academic (Chap. 2).
Pilar, F. (1968). *Elementary quantum chemistry* (2nd ed., 1990). New York: McGraw-Hill.
Pittman, K. M. (1999). Student-generated analogies: Another way of knowing? *Journal of Research in Science Teaching, 36*, 1–22.
Rappoport, L. T., & Ashkenazi, G. (2008). Connecting levels of representation: Emergent versus submergent perspective. *International Journal of Science Education, 30*, 1585–1603.
Sánchez Gómez, P. J., & Martín, F. (2003). Quantum versus 'classical' chemistry in university chemistry education: A case study of the role of history in thinking the curriculum. *Chemistry Education Research and Practice, 4*, 131–148.
Scerri, E. R. (2001). The new philosophy of chemistry and its relevance to chemical education. *Chemistry Education Research and Practice, 2*, 165–170.
Stevens, S. Y., Delgado, C., & Krajcik, J. S. (2010). Developing a hypothetical multi-dimensional learning progression for the nature of matter. *Journal of Research in Science Teaching, 47*, 687–715.
Stieff, M., Ryu, M., Dixon, B., & Hegarty, M. (2012). The role of spatial ability and strategy preference for spatial problem solving in organic chemistry. *Journal of Chemical Education, 89*, 854–859.
Stinner, A. (1995). Science textbooks: Their present role and future form. In S. M. Glynn & R. Duit (Eds.), *Learning science in the schools* (pp. 275–296). Mahwah: Lawrence Erlbaum Associates.
Suidan, L., Badenhoop, J. K., Glendening, E. D., & Weinhold, F. (1995). Common textbook and teaching misconceptions of Lewis structures. *Journal of Chemical Education, 72*, 583–586.
Sutton, C. (1996). Beliefs about science and beliefs about language. *International Journal of Science Education, 18*, 1–18.
Taber, K. S. (1998). An alternative conceptual framework from chemistry education. *International Journal of Science Education, 20*, 597–608.
Talanquer, V. (2006). Common sense chemistry: A model for understanding students' alternative conceptions. *Journal of Chemical Education, 83*, 811–816.
Talanquer, V. (2007). Explanations and teleology in chemistry education. *International Journal of Science Education, 29*, 853–870.
Talanquer, V. (2009). On cognitive constraints and learning progressions: The case of structure of matter. *International Journal of Science Education, 31*, 2123–2136.
Towns, M. H., Raker, J. R., Becker, N., Harle, M., & Sutcliffe, J. (2012). The biochemistry tetrahedron and the development of the taxonomy of biochemistry external representations (TOBER). *Chemistry Education Research and Practice, 13*, 296–306.
Tsaparlis, G. (2001). Molecules and atoms at the centre stage. (Preface to themed issue on: Structural concepts – Contributions from science, science education, history and philosophy of science). *Chemistry Education Research and Practice, 2*, 57–65.
Tsaparlis, G. (2003). Chemical phenomena, chemical reactions: Do students make the connection? *Chemistry Education Research and Practice, 4*, 31–43.

Venville, G., Bryer, L., & Treagust, D. F. (1994). Training students in the use of analogies to enhance understanding in science. *Australian Science Teachers Journal, 40*, 60–68.

Vosniadou, S. (2002). Mental models in conceptual development. In L. Magnani & N. J. Nersessian (Eds.), *Model-based reasoning: Science, technology, values* (pp. 353–368). New York: Kluwer Academic.

Vosniadou, S., & Brewer, W. F. (1994). Mental models of the day/night cycle. *Cognitive Science, 18*, 123–183.

Vosniadou, S., Vamvakoussi, X., & Skopeliti, I. (2008). The framework theory approach to the problem of conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 3–34). New York: Taylor & Francis.

Yifrach, M. (1999). *Definition of chemical literacy and assessment of its attainment in high school chemistry*. Unpublished master's thesis (in Hebrew), Weizmann Institute of Science, Rehovot.

Index

G. Tsaparlis and H. Sevian (eds.), *Concepts of Matter in Science Education*, Innovations in Science Education and Technology 19, DOI 10.1007/978-94-007-5914-5,