Models and Modeling in Science Education

Billie Eilam
John K. Gilbert *Editors*

Science Teachers' Use of Visual Representations

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Part I
Research into Teaching with Visual Representations

1.1 Introduction

The two chapters in this part provide the backdrop against which research studies into key aspects of the practicalities of teaching with visualizations are subsequently presented.

In the first of them, Eilam and Gilbert (this volume, Chap. 1) justify attention being paid to visualizations and identify the themes that make research into science teachers' use of visualizations a matter of great importance. The central role of models in scientific methodology is assumed and visualization is identified as a key component in the creation and employment of all models. This emphasis is gaining ever- greater importance as the ways in which visualizations can be presented with the aid of computers become more accessible and intellectually more powerful, this leading to their heightened role in teaching. The bulk of the chapter is devoted to identifying the myriad factors that may control the effectiveness of that teaching. First, teachers may have, like many of their students, 'alternative conceptions' of the central concepts of science. Where this occurs, the visualizations accompanying them will be, at best, inaccurate and, at worst, misleading to their students. Second, the fragmentation of ideas in the typical school science curriculum, a very common event, means that the relationships between visualizations of the many component concepts in that curriculum will lack a necessary coherence across and between them. Third, teachers' prior knowledge about visualizations as such will, in the absence of previous systematic professional development activities, probably be deficient in some respects. Teachers may well only have a partial knowledge of the conventions that govern the nature of the different types of visualization and the codes of relationship to what they represent (the referents). In particular, teachers may lack an overt awareness of the intellectual demands of the learning tasks that they have to address. These will be governed by the natures of the referents involved and the implications of whether they are: concrete or abstract; explicitly or implicitly identified. Also, are the events in which these referents are involved: simple or complex; linear or cyclic in nature; have a clear directionality or are they in equilibrium. Lastly, and most importantly, at what 'level' are they targeted: the macro, the sub-micro, or the symbolic.

In the second chapter Ainsworth and Newton start by analysing the current state of enquiry in the field: those aspects of visualizations that have been reported in published research studies. They identified all the papers about any aspect of visualization that have appeared in major journals in recent years. They analysed the papers in terms of the research questions they addressed, the modes of visualization inquired into, and the data collection methods employed in those enquiries. To complement this study, they interviewed some practicing school science teachers to identify the nature of the visualizations that they most valued and what they needed to know in order to be able to most effectively use them. Finally, these two studies were brought together to see the relationship between the judgements of priority made by the two populations. Whilst there found to be considerable overlaps between the answers identified in the analysis of the research papers and the judgements of the teachers, there were a number of distinct and major differences between the two. It is concluded that science education research should draw more extensively on the priorities of practitioners if greater use of its outcomes were to be made use of by them. The other side of that coin should be that teachers would then pay more attention to the outcomes of research and to the analytical approaches of the researchers.

Taken together, these two papers suggest that only a relatively small proportion of the possible issues surrounding teachers' use of visualizations have been enquired into. They do suggest that an address to a broader agenda of issues, if teachers saw it to produce worthwhile outcomes, could lead to both an improvement in classroom practice and to the predictive value of theory about the field.

Chapter 1
The Significance of Visual Representations in the Teaching of Science

Billie Eilam and John K. Gilbert

Abstract The natural world is highly dynamic and complex. Scientists aspire to understand this complex world through observations, investigations and inferences. For this purpose, scientists isolate specific phenomena for studying and examine its features through its simplified models and visual representations (VRs). The constructed scientific knowledge is then communicated to the science community through various modalities like, text and image. Socializing students into the world of science therefore, requires educators among other goals, to teach students all about models and representations, to expose students to these representations diversity and characteristics, to use them for promoting the understanding of phenomena and to develop students' ability to think with representations as scientist do. Teachers' task though, is not an easy one, because scientific phenomena and its representations are difficult to grasp; they are highly complex, comprising many components, micro and macro levels with explicit or implicit interactions within and among them, they are concrete or abstract, or are dynamic or static entities. In addition, to develop students' representational competencies teachers themselves have to be fluent, proficient and efficient in these representations use, develop pedagogical-visual-content-knowledge for teaching with visual representations, be aware of the difficulties inherent to the use of representations or their generation, or be able to identify student-related difficulties, those hindering their learning. Because visual representations are widely used to support science teaching, meta representational competence should be developed. However, this need remains an untreated goal, and researchers report students difficulties to learn with visual

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representations. The chapter discusses the difficulties involved in teaching and how visual representations may this goal.

Keywords Visual representations types • Science domain knowledge • Pedagogies • Difficulties in learning science • Teaching with visual representations

The natural world is highly dynamic and complex. Scientists aspire to understand this complex world through observations, investigations and inferences. For this purpose, scientists isolate specific phenomena for studying and examine its features through its simplified models and visual representations (VRs), including for example, iconic pictures or 3D objects, abstract physics formula or a diagram representing a process, as described by Gilbert (2007):

> As scientific enquiry proceeds in any given field, the complexity of the models of exemplar phenomena that are addressed increases progressively, and the aims of the enquiry become ever more ambitious … Models then become vital if the visualization (visual imagery) of entities, relationships, causes, and effects, within exemplar phenomena is to take place. The development of models and representations of them are crucial in the production of knowledge (pp. 10–11).

The constructed scientific knowledge is then communicated to the science community through various modalities like, text and image, being criticized, re-examined and continuously altered in light of new evidence, to become cannon knowledge and constitute a basis for decision making and problem solving in societal lives.

Socializing students into the world of science therefore, requires educators among other goals, to teach students all about models and representations, to expose students to these representations diversity and characteristics, to use them for promoting the understanding of phenomena and to develop students' ability to think with representations as scientist do. Teachers' task though, is not an easy one, because scientific phenomena and its representations are difficult to grasp; they are highly complex, comprising many components, micro and macro levels with explicit or implicit interactions within and among them, they are concrete or abstract, or are dynamic or static entities. In addition, to develop students' representational competencies teachers themselves have to be fluent, proficient and efficient in these representations use, develop pedagogical-visual-content-knowledge (Eilam 2012a) for teaching with VRs (Visual Representations), be aware of the difficulties inherent to the use of representations or their generation, or be able to identify student-related difficulties, those hindering their learning.

Although people's attitude toward the visual shifted positively with the large-scale changes in today's world, especially the major developments in how societies produce, store, and access information, and the increasing impact of modern technology on all facets of our lives, it seems that our visual-related abilities lag behind the wide use of VRs (Pettersson 2009). Indeed, VRs currently dominate school culture, instruction, learning, learning materials and the media. In particular, VRs are widely used to support science teaching, by promoting teachers' ability to describe and simplify phenomena, explain complex concepts and interrelations, demonstrate diverse linear or non-linear processes, present spatial and temporal dimensions of phenomena, and so forth, while aiming to foster students' deep understanding of it.

This extensive classroom use of a large static or dynamic, 2D or 3D different VRs resulted in the need of all students to be able to navigate within and between the different modes of representation while developing 'metavisual capability', which enable them to undertake these demanding tasks (Gilbert 2007). diSessa and Sherin (2000) elaborated on the different cognitive and metacognitive abilities that should be the target for student instruction, using the term "Meta-Representational Competence" which:

> … includes the ability to select, produce, and productively use representations but also the abilities to critique and modify representations and even to design completely new representations. …. We [diSessa and Sherin] add the prefix "meta" to denote our more encompassing aims. We are interested in whatever students know about representations (meta-representations), whether or not it concerns instructed representations, and whether or not it involves the standard school modes of (only) reproduction and interpretation (p. 386).

However, this need remains an untreated goal, as suggested by the vast research showing that many students still experience difficulties to interpret VRs beyond the superficial, to generate efficient VRs, or to perform many of the other skills required for dealing with scientific VRs. Varied reasons were given for these difficulties, like ineffective design of learning materials, the effect of cognitive load, the need to map across different representations and modalities, students' and teachers' deficient knowledge of representing and representations, split attention effect and more. Once these factors effect is revealed, a large effort is invested in treating them in new designs of efficient displays (to name just few, e.g., Ainsworth 2006; Ayers and Sweller 2005; Bodemer et al. 2004; Bowen and Roth 2002; Butcher 2006; De Bock et al. 2003; Eilam and Poyas 2008; Elia et al. 2007; Eshach and Schwartz 2002; Ginns 2006; Moreno and Valdez 2005; Schnotz and Rasch 2005).

The chapter begins with a discussion of today's necessity of using VRs in classrooms due to present day understanding of the various cognitive difficulties involved in the learning and teaching of science. The difficulties involved in teaching science is then analyzed, followed by research-based discussion of VRs as providing support for this complex process. We end with the call for researchers to focus on and increase our insights into issues related to teachers' knowledge of representing and representations, the VR-related pedagogies they apply in their classrooms and their modes of guiding and supporting their students in this area.

1.1 Difficulties Inherent to Teaching Science

Teaching is a highly complex function. The cognitive revolution in education increased and deepened our understanding of learning as a highly complex phenomenon, how it is carried out in different contexts and settings and with diverse learners' background, what kind of factors affect the process, including learners' prior knowledge, tasks structure and cognitive load, or the content studied. It became obvious that each discipline poses to learners different kinds of difficulties, evolving from the nature of its content and objectives.

Science, has always been considered "difficult to teach and study" drawing high achievers to its classrooms. A closer analysis reveals science teaching encounters many problems and together with mathematics was the first subject-matters to introduce visual aids to the learning environment. Science textbooks were always rich in VRs as compared to textbooks in other subjects, most of them were of the iconic pictures and schema drawings types; a variety of models were used in teaching like those of the human skeleton, of different geometrical bodies, or 3D molecule structures; microscopes enabled examination of cross sections of invisible entities; varied movies were used for showing processes and phenomena – like the BSCS (Biology Science Curriculum Studies) short loop films of the 60th, which students could watch repeatedly; the sciences were the first to introduce TV into classrooms, showing scientific phenomena that cannot be presented at school (e.g., far away habitats) and predesigned lessons. All these aids were used mainly for describing structures and linear processes. They were used on the one hand as a magnifying glass to better observe and describe scientific phenomena and notice its details, and on the other hand as a mean for bringing into the classroom phenomena that otherwise cannot be observed hence, enriching students' experiences and increasing their interest in science.

In the last several decades, the design of such visual aids and representations of scientific phenomena involved a deep consideration of students' cognition. They attempt to trigger students' thinking about the phenomena and investigating its function as related to its structure rather than just observing its details. The accumulated research-based body of knowledge about large variety of VRs, their affordances for developing understanding and transfer ability, as well as their possible constraints of learning, enabled the development of a new generation of VRs aiming to promote students' thinking and understanding of science processes and scientific phenomena. These VRs aim to respond to the difficulties inherent in teaching science while seriously considering students' cognitions and learning.

The present chapter will focus on three main issues: (a) the knowledge required for teaching with VRs, (b) the difficulties inherent to science knowledge instruction, and (c) the potential of scientific VRs to promote science teaching as related to these difficulties. It is self-evidence that these topics cannot be considered in isolation and apart from those involved in the instructional process; students and their characteristics (e.g., age, prior knowledge and experiences, interests, abilities), the pedagogies applied (e.g., teachers' visual-pedagogical-content-knowledge, Eilam 2012a), and the context in which teaching is carried out (e.g., the general context – cultural norms, beliefs, and behaviors, as well as the specific learning setting), because effective teaching takes all these factors into account.

1.2 Factors Hindering Science Teaching

Science education aims to present and explain to learners nature and its complex phenomena as well as the way scientists investigate these phenomena, represent their constructed understanding and communicate it to the public, and think with representations to further develop scientific knowledge. So what is it about the teaching (and learning) of the sciences that requires a large variety of representations?

1.2.1 Domain Prior Knowledge and Experiences: Misconceptions, Fragmentation, and Deficiency

The effect of prior knowledge on the learning of any new information is well established and known for a long time. In science this effect is particularly salient due to scientific phenomena, sometimes being counterintuitive, surrounding individuals from their moment of birth, requiring them to make meaning of their environment in order to survive. Studies concerning the development of scientific knowledge suggest that young children hold basic generative theories (or a set of abstract ontological and epistemological beliefs), which provide them with intuitions concerning diverse basic phenomena in this domain, supply the children with domain-specific reasoning, guide their judgments about incidents with respect to scientific phenomena, and allow for the generation of predictions regarding these phenomena behavior (Nakhleh and Samarapungavan 1999). This intuitive knowledge usually differs substantially from adults' knowledge and from canonic scientific claims. First, a general understanding of each particular domain is acquired, including a sensible framework and beliefs. Then, more detailed information and accurate knowledge of the specifics of the relevant phenomenon are evidenced (Keil 1992; Wellman and Gelman 1992).

Young children have been shown to hold intuitive (naive) theories in domains like physics, psychology, and biology (Carey 1985; Keil 1992; Welman and Gelman 1992). However, even if these initial bodies of knowledge are each consistent and coherent, they might still contain multiple explanatory mechanisms, as expressed in the different ways that children, with similar bodies of knowledge, might explain various phenomena. These naïve theories are functional, easily retrieved, and used for explaining and making sense of everyday knowledge; thereby, these theories develop and grow continuously throughout life (Hatano and Inagaki 1994; Keil 1992). However, although these theories are functional and useful in explaining everyday phenomena, they are limited in factual knowledge, in the hierarchically organized categories of disciplinary knowledge, in mechanical causality, and in disciplinary conceptual devices like evolution, photosynthesis, the structure of matter or gravitation. Factual knowledge can be added by accretion, but the acquisition of conceptual devices is performed by a restructuring of knowledge (Hatano and Inagaki 1994). Different theories deals with individual knowledge growth (diSessa 1993; Vosniadou 1994), but all agrees that naïve/intuitive prior knowledge effect the construction of new knowledge in the course of its acquisition, resulting in difficulties and misunderstanding of it, in conflicting pieces of knowledge that are applied according to need and context, and in fallible mental models that affect future comprehension. Indeed, the term ‘misconceptions’ (or alternative frameworks) was first used in relation to the sciences. Many of the revealed misconceptions were shown to be “dragged” over the years without revision till adulthood (e.g., regarding plants as breathing at night and carry out photosynthesis during day; perceiving solids molecules as static). Revealing core misconceptions in science and some reasons for them brought about a fundamental advancement in teaching complex phenomena (e.g., Chi et al. 1994; Eilam 2004, 2012b; Novick and Nussbaum 1981), but probably increased the need for VRs to help overcome some of the basic misconceptions.

To succeed in teaching any discipline, therefore, teachers must be aware of their learners’ existing knowledge and beliefs (Bransford et al. 2000). One example is Jacobson (2001) claim that peoples’ epistemological stance is inherently different than the one required for understanding complex systems hence, requiring support and intentional intervention for overcoming such beliefs. This notion guide researchers in their drive to understand learners’ thinking, curriculum developers in their search for ways to present knowledge to learners, and teachers in their pursuit of effective instructional designs. These same principles hold true for cases in which the newly acquired knowledge/information is presented in a symbolic language different from text – in images.

Two additional teaching difficulties that evolve from students’ domain prior knowledge are this knowledge fragmentation and its frequently being deficient. School curricula involve the instruction across part of the school years of selected topics in science. This raises several issues to be considered: (a) this selection is usually performed by different people that have different perspectives regarding curricula (e.g., what is proper for a certain age group, discipline canonic knowledge and inherent logic) thus is not entirely progressive; (b) even if it seems progressive to experts, we know it does not mean automatically that it is perceived and understood as progressive to students, depending on their knowledge quality and organization; (c) although the sciences are inter-dependent for constructing deep understanding of the complex phenomena, the parallel progressions of mathematics, physics, biology, and chemistry, is not usually considered, resulting in ‘holes’ of superficial understanding, that may hinder further understanding of new materials (e.g., learning ecology requires understanding specific topics in physics and chemistry, which are taught much latter; understanding the cell requires chemistry, learning certain topics in physics requires mathematics); (d) even if in the horizontal curriculum (i.e., science topics studied in a particular class level) some topics in the different sciences are studied simultaneously, knowledge compartmentalization is evidenced and no links are usually made between them, seldom treating topics at the same time using the different lenses of the sciences; and last (e) most students are not motivated to invest efforts in building an organized and richly linked body of knowledge. Such curriculum design usually results in students’ fragmented and deficient domain knowledge, which requires teachers to design VRs-supported appropriate and effective modes of instruction.

1.2.2 Knowledge of Representing and VRs

Teachers are not scientists. In order to achieve the science education goal of using VRs for teaching and thinking like scientists do, teachers have to acquire a broad body of knowledge about the use of representations in science, about representing, about representational characteristics, VRs advantages and constraints. They have to develop pedagogies for teaching visualization to their students, and gradually increase their awareness of their students' ability to use representations, generate, critique and manipulate them. Teachers have to develop pedagogical-visual-content-knowledge (Eilam 2012a); namely, ability to select an efficient VR for teaching a certain topic to students of a particular age, culture and abilities, in a specific context, to achieve a well formulated goal.

This is not an easy task; it requires time and support, which at the moment are not provided to teachers in most teacher training programs as an explicit intentional and well-designed training for content and practices that have to be mastered. In addition, because teachers are deficient in such knowledge, so are their students. Although the use of VRs in classrooms is overwhelming, research show that this use is lacking depth and is problematic, and hence not always result in advanced learning. For example, Eilam (2012a) described teachers' use of VRs, and their use of the blackboard in teaching. Although teachers filled the board with process diagrams, hierarchical diagrams, concept maps and more, they tended to assume that most students can understand and interpret them, and they can "go without say". Examining students' understanding showed that they misinterpreted teachers' intentions they did not notice mistakes done while they copied mindlessly these VRs into their copybooks, and so forth. In the sixth grade, science teachers asked their students to build a model of human respiratory system, "to increase their fun and interest." A quick analysis of these models demonstrated students' deficient understanding of what a model is. An interview with the teachers revealed that no preparatory work has been done with students for this project, resulting in inaccurate products (Eilam 2012a).

The teaching of more complex topics like complex systems, requires the use of simulations, modeling, and other VRs and the application of all aforementioned types of knowledge, including: generic knowledge about the nature of models and representations, domain knowledge, and many related cognitive and metacognitive skills (e.g., reasoning, inquiry) (de Jong et al. 2005). Many claim that teachers are not prepared to handle such complex learning (Hmelo-Sliver 2004; Vick et al. 2005). Lately, some evidence have been reported of teachers' developing awareness and pedagogical-visual-content-knowledge (Anagün and İşcen 2010; Cook 2011; Prain and Waldrip 2006, 2008; Schroeder et al. 2011; Yarden and Yarden 2011).

1.2.3 Knowledge of VRs-Related Tasks

Current learning tasks integrate VRs with texts. To be able to perform such tasks, one has to have knowledge about the particular task-type (e.g., describe something, analyze, predict based on), to have relevant domain knowledge as described above, and to be able to handle the VR in relation to the verbal task – to map between concepts and entities in these analogues. However, students' intentional and guided experiences in learning with multimedia are limited. VRs in learning materials (e.g., textbooks, teachers' generated materials, the internet) frequently appear as isolated, lacking any noticeable connection to the text or a pointer that direct students to explore such relations and the advantages provided by these VRs to the understanding of the juxtaposed text. Many of these VRs are ignored by teachers based on "lack of time" or "content to be covered" and by students, who are not directed to deal with them. If students have to acquire the scientific modes of using VRs, they have to be provided with opportunities to actively be engage in and experience the use of VRs as well as of thinking and solving problems with them.

1.3 The Nature of Scientific Knowledge

The complexity of science knowledge invites the use of VRs to support its teaching and learning, as is described next, according to the complexity level of this knowledge features.

1.3.1 Entities Sizes

Science deals with all natural phenomena, thus with a continuum of entities of all sizes. Atom particles may be found at one end of this continuum. The image of the atom may be obtained through a special technology that is off course, not available at schools thus requires other means for presenting it to students. Its nucleus subparticles cannot be directly observed by any existing technology, although their existence and characteristics may be indirectly inferred from experimental results performed with the new accelerator. These structures are not required in physics only. Their understanding constitutes the basis for understanding the micro-level phenomena in all sciences (e.g., cycles of cell respiration in biology, molecule structures and reactions in chemistry, astronomy). Located at the other end of the size continuum are the universe and its galaxies, where distances are measured in light years, a concept in itself very difficult to grasp. These dimensions too touch upon the understanding of other sciences. For example, it touches on the processes of the evolving life on earth and evolution. This is not to say that all these topics are part of the curriculum, but some of them are and they all shed some light on different curricular issues.

In between these two ends, there are scientific entities and phenomena of all sizes. Parts of them, those which are visible to the naked eye, still require additional means for viewing their inner structures, or micro-level structures. Others may be observed directly only through the use of technology like the microscope for viewing cells, or the telescope for viewing some of the stars. Hence, the understanding and using of visual scales are central to scientific knowledge. Mostly, these scales are not perceived directly, but are mediated by different VRs. For example, researchers assessed the extent to which novice and expert teachers could accurately conceptualize the spatial size of objects and distances presented in VRs. Findings showed that on several tasks both novices and experts revealed a deficient or distorted underlying framework for understanding scale, showing a high magnitude of errors. They held more accurate conceptions of large scales than small ones, probably because they are visible to the eye, and indicated that they conceptualized size from both direct and indirect experiences (i.e., with objects or via equipment) during their formal learning, calling for training teachers to deal with this topic (Jones et al. 2008).

1.3.2 Concreteness and Abstractness, Explicit and Implicit

Scientific entities and phenomena may be concrete-explicit (e.g., plants, materials), concrete but implicit (e.g., bacteria, virus, molecules, diffusion), abstract and the outcomes of their phases or their components being explicit (e.g., matter cycles in nature, feedback mechanisms, chemical reactions, rust, movement), or abstract and implicit – inferred indirectly from outcomes of their effects (e.g., magnetic fields, gravitation, energy cycles in nature). Some researchers reported for example, on students' difficulties to understand the structure of the living cell, which is both 3D and concrete but implicit (Verhoeff et al. 2008), of matter – its structure and molecules mobility (Eilam 2004; Lee et al. 1990; Nakhleh et al. 2005), or of light, heat and electrical current in physics (Slotta et al. 1995). To learn about most of these entities and phenomena, which are not concrete and explicit, teachers have to employ different means; they have to make them observable, and to represent their qualitative and quantitative properties (e.g., interactions, components, quantities ratios, processes, spatial organization), necessitating the use of models, diagrams, charts, schema, graphs, and more.

1.3.3 The Macro and the Micro Levels

All scientific entities and phenomena may be perceived and understood as a single whole, at their macro level. For example, a plant has roots, stem, leaves, flowers – all connected into one functioning structure, or a certain material which is a powder of certain color and dissolves in water. However, to understand this functioning structure, one has to examine its micro level structure and function, the different cells and the organelles in them, or the different molecules comprising the powder. Observing the macro level with no knowledge of its micro-level structure and function, results in a deficient understanding of processes like matter transformations or state of matter, and so forth. Studies have shown that students have a great difficulty to shift between these levels, hindering their ability to understand many scientific phenomena (Chi 2005; Levy and Wilensky 2008). Such shifts may be achieved by the use of different VRs.

1.3.4 Linearity and Simultaneously

Students tend to think linearly and uni-directionally (Leach et al. 1996). This tendency is strengthened by their massive exposure to texts, reading, and verbal descriptions of phenomena, which are all fundamentally linear in nature. Another reason may be the nature of human perceptual system, which is able to focus on a single element at a time while disregarding peripheral simultaneous occurrences, which may be important for understanding of the observed phenomena. However, although many scientific phenomena are described generally as linear (e.g., growth, photosynthesis, feeding chains, protein synthesis, evolution), these are mostly only parts of a larger phenomenon that may be cyclic or multidirectional, with many simultaneous related occurrences (e.g., growth involves many cycles that provide energy and matter to the dividing and transforming cells, photosynthesis is a cyclic process integrated within the larger cycles of organic matter in nature, feeding chains are actually complex feeding webs, protein synthesis is a complex process involving many simultaneous reactions and mechanisms, the complex evolution may be perceived as a tree shape process with multiple branches). Tendency toward linearity may impede the understanding of such complex, mostly implicit, processes. Because classroom discussions are linear, a different mean that would enable the development of a non-linear view of phenomena, have to be employed in science education.

1.3.5 Directionality and Causality Versus Equilibrium

Like in the case of linearity, students tend to perceive scientific phenomena as uni-directional and mono-causal, and fail to identify causes in particular when they are implicit (Grotzer 2005; Grotzer and Bell Baska 2003). Research has provided many evidence of students' teleological thinking, which conceive entity to direct itself toward a particular purpose (e.g., the giraffe's neck was elongated through her stretching it while trying to reach the tree tops for food) (Crawford et al. 2005. Linearity and directionality together hinder students' ability to understand the core concepts of equilibrium and feedback in the sciences (e.g., biology – population size, osmosis; chemistry – reactions, diffusion; physics – state of the matter) as reported by many researchers (Sweeney and Sterman 2007; Eilam 2012b). Here again, educational supports are designed for promoting teachers' ability to teach these concepts in depth.

1.3.6 Simplicity and Complexity

The term simplicity may seldom be used in relation to scientific phenomena, which are never simple. However, it is possible to distinguish between highly complex phenomena like ecosystems or weather changes and the examination of discrete entities or phenomena like how two materials react, the forces acting on an object, or a single level, concrete, directly observed small and limited part of the structure of an entity.

An understanding of the need to include the topic of complex systems in science education evolved in the last few decades following its prevalence in many other domains (e.g., sociology, geography). The realization that (a) many phenomena in science are systemic in nature, and therefore, (b) most of students' identified difficulties are related to the inherent complexity of this topic, attracted researchers' and educators' attention. Many researchers described the characteristics of complex systems in details and examined students'-related difficulties in understanding a phenomenon. Complex systems involve all the aforementioned difficulties and much more, as expressed in its main idea that the whole is more and qualitatively different from the sum of its parts. In the next section we will attend to these characteristics and the related difficulties.

1.3.7 Complex Systems Characteristics

Complex systems are characterized by their many highly diverse, interconnected components (e.g., concrete or abstract, complex or simple, explicit or implicit), and organized in multi-interdependent macro- and micro-levels. By focusing on a particular level of a phenomenon, individuals determine their perception of it, resulting in the distorted view of this phenomenon. Changing quantities of system components interact constantly, mostly in a non-linear manner, within a specific level, between levels, or with the environment, giving rise to visible as well as invisible dynamic processes and a high-order or aggregate behavior. Such systems are typified by multiple indirect complex causalities, and reflect multiple temporal and spatial scales. A small change in its micro-level may result in a large effect and change in its macro-level.

Scientific systems are decentralized; namely, they lack a central control mechanism. However, they may self-organize into global patterns. The emerging aggregate behaviors that evolve from individual components' properties and interactions, usually in implicit non-intuitive ways, are frequently not predetermined or predictable and are qualitatively and quantitatively different from an individual component behavior (Hmelo-Silver and Azavedo 2006; Hmelo-Silver and Pfeffer 2004; Hmelo-Silver et al. 2007; Jacobson 2001; Levy and Wilensky 2008; Penner 2000; Sabelli 2006). Resnick (1996) elaborated on these high order phenomena, explaining that a positive feedback has an important role in decentralized systems – not necessarily bad one – in keeping them in an equilibrium stage, randomness creates order in many self-organizing systems. Random fluctuations act as the seed from which patterns and structures grow, and then the feedback makes these seeds grow. Interactions among elements in one level of a decentralized system give rise to new types of objects at another level, which are frequently very different, causing students to confuse levels. Individual elements (objects) in the emergent phenomena always change (Resnick 1996).

1.3.7.1 Complex Systems and the Teaching-Learning Difficulties

This description of complex systems characteristics and properties intuitively suggests the inherent difficulties in the teaching and learning of this topic. This is in particular true because research show that system thinking, like other cognitive abilities, does not develop spontaneously and naturally, but has to be developed through formal education. But the latter is fragmented and compartmentalizes, hence suppressing student's system thinking.

Sweeney and Sterman (2007) and some other researchers summarized teachers and students' difficulties regarding the dynamicity and complexity of systems. Both teachers and students were found to focus on the behavior of individual entities, ignoring the environment surrounding these entities and that interact with them; they have difficulties to trace multiple causality beyond one way connections, they don't recognize feedback spontaneously (close the loop), but use the term cycles to describe a repeated sequence of events or to describe balancing or reinforcing feedback; they fail to understand positive feedback – that the larger the quantity of an entity is – the greater the rate of growth of this quantity, growing in accelerating rate; they displayed a "inflow focus" bias, assuming stocks can grow by increasing the inflow, without considering the decreasing of outflow, and that inflow equal outflow, without considering accumulations or deficits due to diverse factors acting in the phenomena or in its surroundings; they did not consider close entities before distant ones.

Teachers and students described only limited elements within the immediate boundaries of the examined phenomenon rather than the many factors acting in it; they confuse levels of a system that composes of many interacting parts and copy the attributes of one level to another; people focus on immediate effects and ignore extended indirect effects; they focus on structures rather than on functions, and explain decentralized self-organizing system behavior as centrally controlled (Hmelo-Silver and Pfeffer 2004; Resnick 1996; Sweeney and Sterman 2007; Wilensky and Resnick 1999). Other identified difficulties were students' limited domain knowledge, inability to relate between the model and the phenomena modeled (de jong and van Joolingen 1998), and their inability to recognize incompatibility between modeled outcomes and expected behaviors of the system represented (Hogan and Thomas 2001). Resnick (1996) added to that list, suggesting that students usually consider exogenous factors alone as causing actions, rather than exogenous or endogenous factors. He examined in depth the understanding of emergence in complex systems, and showed that this phenomenon conflicts with both students' teleological beliefs that ascribe purposefulness to events and with people's "centralized mindset" bias, that favor explanations assuming central control and a single causality and is much deeper than a misconception (Resnick 1996).

In light of research findings, Resnick (1996) suggested several indicators for a deep understanding of complex systems. He summarized and suggested that complex systems should be understood: (a) as being a whole that is greater than the parts, (b) as decentralized having no central control (system interactions), (c) as having multiple causes rather than a single one, (d) as possibly displaying a big effect that results from a small action, (e) as displaying a stochastic behavior not completely predictable, (f) as displaying complex actions from simple rules, (g) as being unpurposefulness, nonteleological, and (h) as having equilibrium processes (Resnick 1996). If such understanding should be achieved, educators and teachers have to develop and employ thoughtful pedagogies and a variety of supporting representations.

1.4 VRs for Supporting Science Teaching

We have shown up to this point, that teaching science is complex due to scientific knowledge properties. We will now discuss the many ways VRs may support science teachers' efforts, attending to the specific difficulties described in the previous section.

Researchers suggest that only through the very carefully designed interventions people may come to understand complex phenomena like those found in science (Klopfer 2003; Slotta and Chi 2006; Wilensky and Reisman 2006). Interventions may apply different approaches (e.g., constructivist, collaborative), but most of them integrate the use of VRs or of multiple representations. Such use has been shown to have positive effects with limited costs, due to VRs many advantages in efficiently representing information (Ainsworth 2006; deJong et al. 1998; deVries et al. 2009; Mayer 2005a).

However, studies reported the many difficulties students encounter while learning with VRs. For example, Vosniadou (2010) contended that at least some of these difficulties evolve from the inherent differences between perceptually-based representations and conceptually-based ones – representations of conceptual models, the latter presenting a greater difficulty to students. Such difficulties should be treated by teachers through explanations, training, exercises, well-designed tasks, while scientific content is studied jointly with VRs. Images have the power to capture scientific knowledge, to communicate it to various audiences, and to flexibly produce meaning by their interactions with learners. However, VRs may also hinder learning through superficial and erroneous interpretation or misunderstanding what representing is or the various representation properties. It is up to professional educators and displays designers to enable the productive efficient use of VRs and develop pedagogies for such teaching. We now discuss the many ways in which VRs may decrease the difficulties involved in teaching science contents, in the order they have been presented above.

1.4.1 Entities Sizes

Teachers may use different technologies jointly with a variety of VRs for dealing with the difficulties involved in the sciences size scales. Some of the micro-level phenomena (e.g., cells and some of their organelles, crystals, textures) and the astronomical phenomena may be observed using a simple school microscope or telescopes. Other, smaller or larger scale entities may be observed in pictures, schema, models, animations, and such, representing some of the properties of these entities as observed and inferred through complex technologies or complicated experiments. However, observing different entities does not necessarily promote individual size scales.

Many pictures, schemas etc. in teacher-generated learning materials, in textbooks, or in the media lack any size scales or at least a note about this issue. A joint presentations of entities of different scale-size (e.g., a single schema presenting a sperm and an egg a bit smaller than a zygote, a baby and the adult all on the same size scale) hinders students' understanding of the different size scales involved in science, hindering for example, their ability to differentiate among different levels of phenomena. The same is true for temporal scales, when different phases of a phenomenon located on a developmental scale with equal units between them, giving the impression that the time passed from one phase to another is the same (e.g., different phases of cell division). Adding scales (like in a map, or extent of magnification) near every entity or a note explaining the different images sizes, or a time scale with time duration between different points is proportional to real time – may increase students' awareness of size-related problems, and their understanding of related science issues. Some indirect effects of scales on learning science were also reported; for example, students' difficulties in relating macroscopic observations to microscopic explanations were explained by their perceiving any kind of picture as macroscopic (Liu and Lesniak 2006) and elementary school students and older students were found to lack the awareness of causality particularly when temporal and spatial gaps were evidenced (Grotzer and Baska 2003). Students should be engaged formally in well-designed tasks for promoting their awareness of size scales in the sciences, as done by several researchers (Jones and Taylor 2009; Jones et al. 2008), which at the same time would enhance students' ability to examine VRs critically as related to scale.

1.4.2 Concreteness and Abstractness, Explicit and Implicit

Concrete and explicit entities may be thought of as easy to directly perceive and understand. Assuming that the components of these entities are not necessarily arranged in a perfect symmetry, longitudinal and horizontal cross sections at several locations may help students to imagine their 3D structures. Again, the potential is there, but such images and schema are not easily interpreted by students, while being aware of the specific location of the section within the entity space, and not easily reconstructed into the whole entity. Although such skills may be acquired through the engagement with exercises and related tasks, they are usually lacking from lessons and textbooks that present such sections assuming students can absorb such knowledge independently, affecting students' understanding of the entity (Eilam 2012c).

There are sometimes means to make implicit properties explicit. A good example is the use of the prism for showing the different wavelength or the use of different lenses to demonstrate the behavior of light. Students have to be able to evaluate such evidence and what may be inferred from them, requiring deep knowledge of representing and VRs.

Understanding 3D entities that contain micro structures, or that constitute a part of huge entities (e.g., cells, particles in atom, our galaxy and the sun) frequently requires models (in addition to pictures or schema of different sections in them). Many research studies have reported the difficulties inherent to learning with models (Gilbert 1993; Gilbert and Boulter 2000). Teachers have to allocate lesson time to explain what models are, the differences between them and reality, etc. Models (e.g., those prepared by students) can be highly accessible, cheap and easy to use. But if prepared for the mere reasons of engaging students, having fun, showing activity rather than promote their understanding of the modeled phenomena – it may be better not to use them at all (Eilam 2012a).

Implicit processes and some structures may be represented by diagrams or charts. These representational modes represent qualitative information – elements and their interrelationships – and provide an integrated visual argument. Diagrams are schematic pictures of events or phenomena represented spatially by conventional symbols used in Western culture (e.g., arrows, cycles). Charts specify qualitative relationships among various entities represented by single words or short phrases as categories (e.g., tree charts, flow charts, hierarchical charts). Both convey meaning through the exploration of two-dimensional space, representing parts in a whole, reducing efforts by facilitating identification of implicit and explicit relationships among presented elements (Kosslyn 2006; Larkin and Simon 1987). Researchers reported of learners' better understanding and more accurate construction of mental models of the heart and circulatory system when they learned with diagrams, and in particular those that were simple and highlighted the critical relations in the domain (Ainsworth 2008; Butcher 2006).

Pictures as a mean to decrease science teaching complexity are almost self-evidence. In addition to supporting learners' construction of mental models of a phenomenon, and raising interest and motivation, pictures are concise and holistic rather than the linear description of the phenomenon; pictures may direct learners' attention to certain aspects of the phenomenon, support learners' interpretation and comprehension of a difficult part of the phenomenon (interpretational pictures), may increase coherency of the phenomenon under investigation (organizational pictures), and increase retrieval by establishing nonverbal codes alongside verbal ones hence, also enhance recall of this information and the acquisition of higher-order concepts and skills by making information more accessible (transformational pictures) (Carney and Levin 2002; Hegarty and Just 1989; Levin and Mayer 1993; Levin et al. 1983; Peeck 1987).

Elia and Philippou (2004) defined informational pictures as containing information necessary for solving problems in mathematic. They found that the representational, organizational, and informational pictures were all helpful in supplying needed information for solving problems, depicting situations in space, and organizing sixth grade students' thinking.

However, some researchers indicated the constraints pictures may impose on learning. For example, they may divert attention to irrelevant elements or highlight trivial elements at the expense of central ones (Brookshire et al. 2002; Colin et al. 2002). Another consideration is the selection of pictures for learning materials, which is performed by individuals whose concerns and attentions may be very different from those of their students. Such images may lack relevancy to student and hinder their learning, as suggested by the coherence principle of learning with multimedia (Mayer 2005a). Last, Weidenmann (1989) suggested that pictures are often perceived as easily and quick to encode therefore, learners examine them superficially and inadequately. At times, colors used in pictures and in particular in schematic drawings may mislead students. Such colors are usually used to emphasize different components, but are frequently different from colors (if at all exist) in reality. Good examples are the blue water, the red and blue blood or colored atoms.

These studies suggest that teachers should be aware of the benefits and constraints inherent to pictures and other kinds of more abstract and sophisticated VRs, and carefully and mindfully select them to facilitate students' gains. Teachers also have to promote students awareness of such features, to avoid VRs erroneous interpretation.

1.4.3 The Macro and the Micro Levels, Linearity and Simultaneously

The issues of levels and linearity are inherently different but may be represented using similar principles, thus will be discussed jointly. Differently from processes, structures lack the temporal dimension. Different kinds of iconic VRs (e.g., photographs, pictures, schema) may be used for showing the different levels composing the structures of a phenomenon. Mostly, they employ a similar technique that is highly familiar to learners due to its prevalence in learning materials and the media. Namely, a certain location of a macro-level phenomenon is enlarged in a distinct picture/schema that "exit" from it and represent its micro-level structure like an examination of a small macro-level part under a microscopic lens. Other VRs may represent the different phenomenon levels in separate pictures or schema, leaving it for learners to construct a mental model of these different levels as combining the whole, one that would allow them to shift between levels as is required. Schematic drawings different sections in a structure may be used for representing the internal structure of an entity. The interpretation of such sections (e.g., cross or longitudinal section) require some experience, training and spatial ability.

Representations of processes are more sophisticated because they involve the temporal dimension, they occur over time. They present the various functions carried out by/in phenomena. These may be linear, non-linear or simultaneous in nature, having one phase or many, occurring in the macro-level or the micro-level of phenomena. Here temporal scales are most important – and students have to (a) perceive the differences between long-term and short term phenomena and its implications, and (b) have to be aware of different time durations of different phases of a single process. Metacognitive awareness of temporal scales is therefore, as important as awareness of size scales. Processes are usually represented using spatial diagrams or charts with arrows that lead observers through the process as it occurs. For example, the presence of arrows on machine diagrams was found to increase interpreters' use of motion-oriented language to describe machines' functions, whereas interpreters used more structural descriptions when diagrams lacked arrows (Heiser and Tversky 2006). Being spatial, diagrams are perceived as a whole and may represent any kind of process, avoiding the linear verbal or textual descriptions of the phenomena.

Cycles are another type of a diagram, widely employed by the sciences (e.g., cycle of life in biology, cycles of reactions in chemistry). Usually, they represent the macro-level or the micro-level of a process or integrate both levels based on the same principles as described above for pictures and schema. Namely, the micro-level of the phenomenon is detailed at the relevant specific points of the macro-level cycle. However, cycles have been found to be perceived and used by many learners erroneously. For example, many fail to perceive the cycle as representing millions of simultaneous reactions, as representing the macro-level only and as simplifying the whole process (i.e., the outcomes of the micro-level reactions), as representing processes that may be performed in various locations (e.g., cycles of matter and energy in ecology), or to understand that cycles will go on repeatedly due to the lack of materials equilibrium in it (Eilam 2012b; Hmelo-Silver and Azevedo 2006). Students understand the cycle of life as representing the phases a single organism is going through (e.g., fertilized egg to caterpillar, to a pupa, and a butterfly, which return to the egg). But, actually cycles like this in biology represent the phases that a population of organisms rather than a single one are going through. Although the cycle is closed, the adult do not develop into an egg … (Eilam 2012c).

Processes may also be represented as a series of static pictures/schemas, each representing the structure and the features of a stage/phase in the process (Tufte 1997). Such representations require learners to invest efforts in the construction of the process and its stages from the changes observed in each state, but present to them an iconic dimension of the process, which is lacking in abstract diagrams.

Dynamic representations like videos or animations have the potential to overcome these difficulties. Generally, they reduce abstraction, present phenomena holistically, and thus appear to promote understanding of temporal-related phenomena like processes (Park and Hopkins 1993; Rieber and Kini 1991). However, animations are preferred to video and movies of phenomena because the latter: (a) impose on learners a large amount of information at any point in time, thereby initiating a high cognitive load which reduce performance by leaving deficient amount of resources for this information processing; (b) present their information fast, making it impossible for learner to focus their attention on most of it; and (c) much of the information is usually irrelevant thus impeding performance according to the coherency principle (Mayer 2005a). Researchers developed ways to overcome these difficulties. For example, introducing repetitions to the observed phenomena, making it interactive, highlighting important information in it, enabling a mechanism of students-controlled pace, giving students previews with explanations about what they are going to see, all found to promote students' learning (Mayer et al. 2005; Michel et al. 2007; Schwan and Riempp 2004). Animations overcome some of these problems by displaying simulated processes and changes over time, rather than phenomena in the real world and by presenting the segmentation of the phenomenon rather than its whole (Mayer 2005b). Thus, only core and simplified information is presented rather than reality. Animations may present a function of a concrete structure (e.g., how the heart pumps blood, how molecules transfer across a cell membrane) or an abstract one (e.g., how forces act in an earthquake). However, as found for most VRs, animations' affordances depend to a great extent on their design characteristics, on students' characteristics, and on the specific circumstances (Ainsworth 2008; Bodemer et al. 2004; Hegarty et al. 2002; Höffler and Leutner 2007; Lewalter 2003; Lowe 2003; Schnotz and Rasch 2005; Tversky et al. 2002).

To sum, although many different VRs may serve the purpose of promoting students' understanding of the dimensions of phenomena discussed in this section (i.e., macro- and micro-levels, linear, non-linear and simultaneous processes), each one of them requires teachers' guidance and students' metacognitive awareness of their affordances and constraints in the specific circumstances.

1.4.4 Directionality, Causality, Equilibrium and Complex Systems

Directionality, Causality, equilibrium and complex systems are all dynamic phenomena. As described above, dynamic phenomena may be presented by a series of static images progressing over time, but this kind of VRs requires students' investment of effort to combine the phases into a whole process. In addition, such a representation cannot capture the complexity involved in complex systems as described above. Animations are useful for presenting to students simple processes, their directionality, causality and even their equilibrium state (e.g., diffusion, different cycles). However, understanding the many phenomena involved in complex systems requires other means. Some researchers used static models for learning limited size complex systems. Others, developed and designed computerized models. Among the most useful devices are computer simulations, found to promote students' understanding of at least some phenomena in complex systems.

Researchers argued that the use of system modeling promotes students' ability to relate between different phenomena levels, which are complex, not directly perceivable, and often are abstracted in models, as well as promotes the scientific way of thinking (Gilbert 1993; Gilbert and Boulter 2000). According to Harrison and Treagust (2000), models in system thinking are driven from system theory, starting from scale models depicting structures or idealized structure of phenomena, the more concrete presentations of it, and proceeding toward more general and theoretical system models. Clement (2000) included in this pathway also the internal representation of phenomena – students' idiosyncratic mental models – as a starting point.

Different kinds of modeling have been found effective in promoting students' understanding of complex systems. One approach encourages students' self-constructed models and their exploration rather than dealing with ready-made ones, which effectively support their conceptual development (Abell and Roth 1995; Coll and Taylor 2005). Such self-constructed models may be physical, abstract, or live models. An example for the use of physical and abstract models is the study that examined the teaching of the living cell (Verhoeff et al. 2008). Students' fragmented and deficient knowledge about this system was explained by the aforementioned difficulties. The model-based intervention resulted in students' improvement of their systemic understanding of several dimensions of the cell. Others used self-constructed live models for promoting students' understanding of ecology for example, reporting a significant increase in most students' understanding of core concepts of the feeding relation system, nested in the larger ecosystem (Eilam 2012b).

Simulations represent and imitate the chaotic and ambiguous environment of the real world, based on a constructed model of it. By performing explorative interaction with simulations, learners are able to test and visualize their hypotheses, develop models about the system, modify them and establish relations among variables. It also enable them to experience skills like, planning, testing, analyzing, and critiquing models, while engaging in multivariable reasoning like, controlling variables, identifying causal relations, explaining simultaneous effects of multiple variables. Modeling by simulations enables students to experience the dynamic and ongoing nature of science (Kuhn 2005; Penner 2001). Teachers benefit from students' interactions with simulations, because such an activity reveals their perceptions of the investigated phenomenon and promote teachers' ability to improve students' understanding (Jacobson and Wilensky 2006). These researchers contended that for robust understanding of complex systems both agent-based and aggregate perspective are required, enabling students shifting between the bottom-up agent-based approach and the top-down aggregate perspective (e.g., the StarLogo – Resnick 1996; the agent-based simulations of population growth or predator and prey – Wilensky; air pollution – Wu 2010).

Few researchers integrated various means, including visual means, to promote their students' understanding of different aspects of complex systems (e.g., Hmelo-Silver et al. 2007). These authors engaged middle school students with inquiry of an aquarium system using RepTools, which contains different artifacts like hyper-media materials, physical models, netLogo computer models that exhibit a macro view of the aquarium studies and a micro view of the N cycle in it. Indeed, students' knowledge improved significantly.

1.5 Final Thoughts

The chapter presented the difficulties involved in the teaching of science. We have discussed the many challenges science concepts and theories impose on teachers learners, and suggested that the use of VRs may benefit both teaching and learning processes, as is supported by many studies. This richness of VRs described above and their many proven potential affordances to the learning of science are encouraging regarding what can be expected in science classrooms presently and in the future. However, we also emphasized that in addition to benefits, different VRs or some of their properties may constraint learning in diverse ways. Another point is that the quality of teaching and learning is not determined by the VRs used and their properties alone; it is the result of complex interactions between teachers' and teaching approaches, students' characteristics – their knowledge, beliefs and relevant skills, the characteristics of the learning materials – including the content, tasks, and VRs, and the wider milieu – like cultural background. Hence, each VR has to be carefully and mindfully selected by teachers to accommodate these many intervening factors. Such deliberation requires a deep knowledge of VRs and of representing, as well as students' abilities to interpret and deal with VRs. Teachers' role in mediating between VRs, contents and students' learning is central to learning with VRs. Presently, teachers' professional development programs are deficient in the opportunities and experiences they provide to teachers, resulting in teachers' lacking knowledge that would enable them a full utilization of the existing materials.

Just as teachers develop pedagogical content knowledge for teaching different content (Shulman 1986), so they have to develop pedagogical-visual-content-knowledge (Eilam 2012a, b, c) for selecting efficient VRs for specific students, for teaching a particular content, in a certain milieu. As described by Shulman (1986, pp. 8–9) pedagogical content knowledge:

> represents the blending of content and pedagogy into an understanding of how particular topics, problems, or issues are organized, represented, and adapted to diverse interests and abilities of learners and presented for instruction … [it constitutes] the most useful forms of representations, the most powerful analogies, illustrations, examples, explanations, and demonstrations – the ways of representing and formulating the subject that makes it comprehensible for others.

Such pedagogical-visual-content-knowledge would promote considerably teaching processes and thus also students' learning, while at the same time enhances students' representational competencies, preparing them for current visual world.

There are other problems to be considered while recommending the use of diverse VRs in science teaching. For example, the limited use of VRs designed for specific interventions. Frequently, learning with such VRs declines following an intervention completion, depending on the involved teachers. Another problem is that many schools over the world have a very limited access to more sophisticated VRs that may support teachers in the instruction of complex and dynamic concepts. They are frequently dependent on teachers'-generated VRs presented in learning materials or on the classroom board. Textbooks in certain places are often colorless and deficient with good visualizations. In addition, most of the VRs designed in Western countries are for use in these parts of the world, disregarding possible cultural effects. It is up to local teachers to adapt them to their students' needs, requiring again a deep understanding of VRs and representing. Hence, even if a VR is represented for free on the Internet, it may require the introduction of changes to become widespread, at least some linguistic changes. On top of all these, the dream of every child having a computer is not yet realized in most parts of the world, not even a computer in every classroom. Deficient technology in classrooms makes VRs (e.g., in the Internet, constructed simulations) even more difficult to access and utilize.

Other sources for efficient science visual materials and programs are TV and museums, which are more accessible to teachers and students. However, it is not clear how many of the recommended programs, those requiring students' invested efforts, are actually observed by students and how much they are able to learn from them without teachers' guidance. Museums afford students many interesting experiences, but they are not available in every city or town, they cost money, and schools limit out-of-school days due to its "harming" the learning of other subject-matters. Last, as for TV, to benefit from a visit to a science museum students have to be guided while being engaged in hands-on activities, to make sense of the represented phenomena.

Thus, there are VRs and effective designs ready to be used, but they require resources for obtaining and changing them to fit local needs as well as teachers' ability to utilize their potential in the course of instruction. To make this happen sooner, we focus on science teachers as they act in their natural classroom environment. We pioneered in this book the presentation of research knowledge about teachers' practical-visual-content knowledge and their use of VRs in their classroom, and especially in different countries in the world, and different cultural milieus. We hope it will promote science teaching everywhere.

References

Abell, S. K., & Roth, M. (1995). Reflections on a 5th grade science lesson: Making sense of children's understanding of scientific models. *International Journal of Science Education, 17*, 59–74.

Ainsworth, S. E. (2006). DeFT: A conceptual framework for considering learning representations. *Learning and Instruction, 16*, 183–198.

Ainsworth, S. E. (2008). How do animations influence learning? In H. Robinson & G. Schraw (Eds.), *Recent innovations in educational technology that facilitate student learning* (pp. 37–67). Charlotte: Information Age.

Anagün, Ş. S., & İşcen, C. F. (2010). Pre-service teachers' perceptions and preferences about visualization. *Procedia Social and Behavioral Sciences, 2*, 2227–2232.

Ayers, P., & Sweller, J. (2005). The split-attention principle in multimedia learning. In R. E. Mayer (Ed.), *Cambridge handbook of multimedia learning* (pp. 135–146). New York: Cambridge University Press.

Bodemer, D., Ploetzner, R., Feueelein, I., & Spada, H. (2004). The active integration of information during learning with dynamic and interactive visualizations. *Learning and Instruction, 14*, 325–341.

Booth Sweeney, L., & Sterman, J. D. (2007). Thinking about systems: Student and teacher conceptions of natural and social systems. *System Dynamics Review, 23*(2/3), 285–312.

Bowen, G. M., & Roth, W. M. (2002). Why students may not learn to interpret scientific inscriptions? *Research in Science Education, 32*, 303–327.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academic Press.

Brookshire, J., Scarff, L. F. V., & Moses, L. E. (2002). The influence of illustrations on children's book preferences and comprehension. *Reading Psychology, 23*(4), 323–339.

Butcher, K. R. (2006). Learning from text with diagrams: Promoting mental model development and inference generation. *Journal of Educational Psychology, 98*(1), 182–197.

Carney, N. R., & Levin, R. J. (2002). Pictorial illustrations still improve students' learning from text. *Educational Psychology Review, 14*(1), 5–26.

Carrey, S. (1985). *Conceptual change in childhood*. Cambridge, MA: MIT Press/Bradford.

Chi, M. T. H. (2005). Common sense conceptions of emergent processes: Why some misconceptions are robust. *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.

Clement, J. (2000). Model-based learning as a key research area for science education. *International Journal of Science Education, 22*(9), 1041–1053.

Colin, P., Chauvet, F., & Viennot, L. (2002). Reading images in optics: Students' difficulties and teachers' views. *International Journal of Science Education, 24*(3), 313–332.

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

Cook, M. (2011). Teachers' use of visual representations in the science classroom. *Science Education International, 22*(3), 175–184.

Crawford, B. A., Zembal-Saul, C., Munford, D., & Friedrichsen, P. (2005). Confronting prospective teachers' ideas of evolution and scientific inquiry using technology and inquiry-based tasks. *Journal of Research in Science Teaching, 42*(6), 613–637.

De Bock, D., Verschaffel, L., Janssen, D., VanDooren, W., & Claes, K. (2003). Do realistic contexts and graphical representations always have a beneficial impact on students' performance? Negative evidence from a study on modeling non-linear geometry problems. *Learning and Instruction, 13*, 441–463.

De Jong, T., & van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research, 68*(2), 179–201.

de Jong, T., Ainsworth, S., Donson, M., van der Hultst, A., Levonen, J., et al. (1998). Acquiring knowledge in science and mathematics: The use of multiple representations in technology-based learning environments. In M. W. van Someren, P. Reiman, H. P. A. Boshuizen, & T. de Jong (Eds.), *Learning with multiple representations* (pp. 9–40). Oxford: Elsevier Science.

de Jong, T., Beishuizen, J., Hulshof, C., Prins, F., van Rijn, H., & van Somersen, M. (2005). Determinants of discovery learning in a complex situation learning environment. In P. Gardenfors & P. Johansson (Eds.), *Cognition, education and communication technology* (pp. 257–283). Mahwah: Lawrence Erlbaum.

deVries, E., Demetriadis, S., & Ainsworth, S. (2009). External representations for learning. In N. Balacheff, S. Ludvigsen, T. de Jong, A. Lazonder, S. Barnes, & L. Mondandon (Eds.), *Technology enhanced learning: Principles and products* (pp. 137–154). Dordrecht: Springer.

diSessa, A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*, 105–225.

diSessa, A. A., & Sherin, B. L. (2000). Meta-representation: An introduction. *Journal of Mathematical Behavior, 19*, 385–398.

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*(10), 970–993.

Eilam, B. (2012a). *Teaching, learning, and visual literacy: The dual role of visual representation in the teaching profession*. New York: Cambridge University Press.

Eilam, B. (2012b). System thinking and feeding relations: Learning with a live ecosystem model. *Instructional Science, 40*(2), 213–239.

Eilam, B. (2012c). Chapter 4: Possible constraints of visualization in biology: Challenges in learning with multi-media. In D. Treagust & C.-Y. Tsui (Eds.), *Multiple representations in biological education* (The series of models and modeling in science education, pp. 55–73). Dordrecht: Springer.

Eilam, B., & Poyas, Y. (2008). Learning with multiple representations: Extending multimedia learning beyond the lab. *Learning and Instruction, 18*(4), 368–378.

Elia, I., & Philippou, G. (2004). The functions of pictures in problem solving. *Proceedings of the 28th Conference of the International Group for the Psychology of Mathematics Education, 2*, 327–334.

Elia, I., Gagatsis, A., & Demetriou, A. (2007). The effects of different modes of representation on the solution of one-step additive problems. *Learning and Instruction, 17*, 658–672.

Eshach, H., & Schwartz, J. L. (2002). Understanding children's comprehension of visual displays of complex information. *Journal of Science Education and Technology, 11*(4), 333–346.

Gilbert, J. (1993). *Models and modelling in science education*. Hatfield: Association of Science Education.

Gilbert, J. K. (2007). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 9–27). Dordrecht: Springer.

Gilbert, J., & Boulter, C. (Eds.). (2000). *Developing models in science education*. Dordrecht: Kluwer.

Ginns, P. (2006). Integrating information: A meta-analysis of the spatial contiguity and temporal contiguity effects. *Learning and Instruction, 16*, 511–525.

Grotzer, T. (2005). The role of complex causal models in students' understanding of science. *Studies in Science Education, 41*, 117–166.

Grotzer, T. A., & Bell Baska, B. (2003). How does grasping the underlying causal structures of ecosystems impact students' understanding? *Journal of Biological Education, 38*(1), 16–29.

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.

Hatano, G., & Inagaki, K. (1994). Young children's naive theory of biology. *Cognition, 50*, 171–188.

Hegarty, M., & Just, M. A. (1989). Understanding machines from text and diagrams. In H. Mandl & J. R. Levin (Eds.), *Knowledge acquisition from text and pictures* (pp. 171–194). Amsterdam: Elsevier Science.

Hegarty, M., Narayanan, N. H., & Freitas, P. (2002). Understanding machines from multimedia and hypermedia presentations. In J. Otero, A. C. Greaser, & J. Leon (Eds.), *The psychology of science text comprehension* (pp. 357–384). Mahwah: Lawrence Erlbaum.

Heiser, J., & Tversky, B. (2006). Arrows in comprehending and producing mechanical diagrams. *Cognitive Science, 30*(3), 581–592.

Hmelo-Silver, C. E. (2004). Problem-based learning: What and how students learn? *Educational Psychology Review, 16*, 235–266.

Hmelo-Silver, C. E., & Azevedo, R. A. (2006). Understanding complex systems: Some core challenges. *Journal of the Learning Science, 15*, 53–61.

Hmelo-Silver, C. E., & Pfeffer, M. G. (2004). Comparing experts 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. (2007a). Fish swim, rocks sit, and lungs breathe: Expert-novice understanding of complex systems. *Journal of the Learning Sciences, 16*, 307–331.

Hmelo-Silver, C. E., Liu, L., Gray, S., Finkelstein, H., & Schwartz, R. (2007b). *Enacting things differently: Using NetLogo models to learn about complex systems.* Paper presented at the Biennial meeting of European Association for Research on Learning and Instruction. Hungary: Budapest.

Höffler, T. N., & Leutner, D. (2007). Instructional animation versus static pictures: A meta-analysis. *Learning and Instruction, 17*, 722–738.

Hogan, K., & Thomas, D. (2001). Cognitive comparisons of students' systems modeling in ecology. *Journal of Education and Technology, 10*(4), 319–345.

Jacobson, M. J. (2001). Problem solving, cognition, and complex systems: Differences between experts and novices. *Complexity, 6*(3), 41–49.

Jacobson, M. J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *Journal of the Learning Sciences, 15*(1), 11–34.

Jones, M. G., & Taylor, A. R. (2009). Developing a sense of scale: Looking backward. *Journal of Research in Science Teaching, 46*(4), 460–475.

Jones, M. G., Tretter, T., Taylor, A., & Oppewal, T. (2008). Experienced and novice teachers' concepts of spatial scale. *International Journal of Science Education, 30*(3), 409–429.

Keil, F. C. (1992). Chapter 4: The origin of an autonomous biology. In M. R. Gunnar & M. Maratsos (Eds.), *Modularity and constraints in language and cognition* (The Minnesota symposia on child psychology, Vol. 25, pp. 103–137). Hillsdale: Lawrence Erlbaum.

Klopfer, E. (2003). Technologies to support the creation of complex systems models – Using StarLogo software with students. *Biosystems, 71*(1–2), 111–122.

Kosslyn, S. M. (2006). *Graph design for the eye and mind*. Oxford/New York: Oxford University Press.

Kuhn, D. (2005). *Education for thinking*. Cambridge, MA: Harvard University Press.

Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth 10000 words. *Cognitive Science, 11*(1), 65–99.

Leach, J., Driver, R., Scott, P., & Wood-Robinson, C. (1996). Children's ideas about ecology: Vol. 2. Ideas found in children aged 5–16 about the cycling of matter. *International Journal of Science Education, 18*, 19–34.

Lee, O., Eichinger, C. D., Anderson, W. C., Berkheimer, D. G., & Blakeslee, D. T. (1990). Changing middle school students' conceptions of matter and molecules. *Journal of Research in Science Teaching, 30*, 249–270.

Levin, J. R., & Mayer, R. E. (1993). Understanding illustrations in texts. In B. K. Britton, A. Woodward, & M. Binkley (Eds.), *Learning from textbooks: Theory and practice* (pp. 95–113). Hillsdale: Lawrence Erlbaum.

Levin, J. R., Shriberg, L. K., & Berry, J. K. (1983). A concrete strategy for remembering abstract prose. *American Educational Research Journal, 20*(2), 277–290.

Levy, S. T., & Wilensky, U. (2008). Inventing a "mid level" to make ends meet: Reasoning between levels of complexity. *Cognition and Instruction, 26*, 1–47.

Lewalter, D. (2003). Cognitive strategies for learning from static and dynamic visuals. *Learning and Instruction, 13*, 177–189.

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.

Lowe, R. K. (2003). Animation and learning: Selective processing of information in dynamic graphics. *Learning and Instruction, 13*, 157–176.

Mayer, R. E. (Ed.). (2005a). *Cambridge handbook of multimedia learning*. New York: Cambridge University Press.

Mayer, R. E. (2005b). Principles for managing essential processing in multimedia learning: Segmenting, pretraining, and modality principles. In R. E. Mayer (Ed.), *Cambridge handbook of multimedia learning* (pp. 169–182). New York: Cambridge University Press.

Mayer, R. E., Hegarty, M., Mayer, S., & Campbell, J. (2005). When static media promote active learning: Annotated illustrations versus narrated animations in multimedia. *The Journal of Experimental Psychology, 11*(4), 256–265.

Michel, E., Roebers, C. M., & Schneider, W. (2007). Educational films in the classrooms: Increasing the benefit. *Learning and Instruction, 17*, 172–183.

Moreno, R., & Valdez, A. (2005). Cognitive load and learning effects of having students organize pictures and words in multimedia environments: The role of student interactivity and feedback. *Educational Technology Research and Development, 53*(3), 35–45.

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., & Saglam, Y. (2005). Middle school students' beliefs about matter. *Journal of Research in Science Teaching, 42*(5), 581–612.

Novick, S., & Nussbaum, J. (1981). Pupils' understanding of the particulate nature of matter: A cross-age study. *Science Education, 65*(2), 187–196.

Park, O. C., & Hopkins, R. (1993). Instructional conditions for using dynamic visual displays: A review. *Instructional Science, 21*, 227–449.

Peeck, J. (1987). The role of illustrations in processing and remembering illustrated text. In D. M. Willows & H. A. Houghton (Eds.), *The psychology of illustration* (Basic research, Vol. 1, pp. 115–151). New York: Springer.

Penner, D. E. (2000). Explaining systems: Investigating middle school students' understanding of emergent phenomena. *Journal of Research in Science Teaching, 37*(8), 784–806.

Penner, D. E. (2001). Cognition, computers, and synthetic science: Building knowledge and meaning through modeling. *Review of Research in Education, 25*, 1–35.

Pettersson, R. (2009). Visual literacy and message design. *TechTrends, 53*(2), 38–40.

Prain, V., & Waldrip, B. (2006). An exploratory study of teachers' and students' use of multi-modal representations of concepts in primary science. *International Journal of Science Education, 28*(15), 1843–1866.

Prain, V., & Waldrip, B. (2008). A study of teachers' perspectives about using multimodal representations of concepts to enhance science learning. *Canadian Journal of Science, Mathematics, and Technology Education, 8*(1), 5–24.

Resnick, M. (1996). Beyond the centralized mindset. *The Journal of the Learning Sciences, 5*(1), 1–22.

Rieber, L. P., & Kini, A. S. (1991). Theoretical foundations of instructional applications of computer-generated animated visuals. *Journal of Computer-Based Instruction, 18*, 83–88.

Sabelli, N. H. (2006). Complexity, technology, science, and education. *Journal of the Learning Science, 15*, 5–9.

Schnotz, W., & Rasch, T. (2005). Enabling, facilitating and inhibiting effect of animations in multimedia learning: Why reducing of cognitive load can have negative results on learning. *Educational Technology Research and Development, 53*(3), 47–58.

Schroeder, S., Richter, T., McElvany, N., Hachfeld, A., Baumert, J., Schnotz, W., Horz, H., & Ullrich, M. (2011). Teachers' beliefs, instructional behaviors, and students' engagement in learning from texts with instructional pictures. *Learning and Instruction, 21*, 403–415.

Schwan, S., & Riempp, R. (2004). The cognitive benefit of interactive videos: Learning to tie nautical knots. *Learning and Instruction, 14*, 293–305.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*, 4–14.

Slotta, J. D., & Chi, M. T. H. (2006). Helping students understand challenging topics in science through ontology training. *Cognition and Instruction, 24*(20), 261–289.

Slotta, D. J., Chi, M. T. H., & Joram, E. (1995). Assessing students' misconceptions of physics concepts: An ontological basis for conceptual change. *Cognition and Instruction, 13*(3), 373–400.

Sweeney, B. L., & Sterman, J. D. (2007). Thinking about systems: Student and teacher conceptions of natural and social systems. *System Dynamics Review, 23*(2/3), 285–312.

Tufte, E. R. (1997). *Visual explanations: Images and quantities, evidence and narrative*. Cheshire: Graphic Press.

Tversky, B., Bauer-Morrison, J., & Bétrancourt, M. (2002). Animation: Can it facilitate? *International Journal of Human-Computer Studies, 57*, 247–262.

Verhoeff, R. P., Waarlo, A. J., & Boersma, K. T. (2008). Systems modeling and the development of coherent understanding of cell biology. *International Journal of Science Education, 30*, 543–568.

Vick, J. E., Azevedo, R., & Hofman, N. S. (2005, April). *Expert-novice differences in the understanding and detection of self-regulated learning with hypermedia.* Paper presented at the annual meeting of the American Educational Research Association, Montreal.

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

Vosniadou, S. (2010). Instructional considerations in the use of external representations. The distinction between perceptually based depictions and pictures that represent conceptual models. In L. Verschaffel, E. De Corte, T. de Jong, & J. Elen (Eds.), *Use of representations in reasoning and problem solving. Analysis and improvement* (pp. 36–54). London/New York: Routledge.

Weidenmann, B. (1989). When god pictures fail: An information-processing approach to the effect of illustrations. In H. Mandl & J. R. Levin (Eds.), *Knowledge acquisition from text and pictures* (pp. 157–171). Amsterdam: Elsevier.

Wellman, H. M., & Gelman, S. A. (1992). Cognitive development: Foundational theories of core domains. *Annual Review of Psychology, 43*, 337–375.

Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic system perspective to making sense of the world. *Journal of Science Education and Technology, 8*(1), 3–18.

Wilensky, U., & Reisman, K. (2006). Thinking like a wolf, a sheep, or a firefly: Learning biology through constructing and testing computational theories – an embodied modeling approach. *Cognition & Instruction, 24*(2), 171–209.

Wu, H.-K. (2010). Modeling a complex system: Using novice-experts analysis for developing an effective technology-enhanced learning environment. *International Journal of science Education, 32*(2), 195–219.

Yarden, H., & Yarden, A. (2011). Studying biotechnological methods using animations: The teacher's role. *Journal of Science Education and Technology, 20*, 689–702.

Chapter 2
Teaching and Researching Visual Representations: Shared Vision or Divided Worlds?

Shaaron Ainsworth and Len Newton

Abstract The relationship between research and practice is highly controversial and many reports describe a gap between the priorities of educational research and those of teachers. Our research explored the extent of this gap in the specific area of visual representation in science education. To identify research priorities, we searched educational databases in the years 2010–2012 and identified 401 journal papers that addressed visual representation in science education. These were coded in terms of their research questions, representations, research methods and disciplinary domains. In addition, six teachers were interviewed about their use of visual representations in the classroom, their priorities and whether and how they engaged with research. Findings revealed that both researchers and teachers considered visual representation to be extremely important across many aspects of science education. They also discovered many points of overlap in terms of shared interests and questions, in some of the representations mostly frequently referenced, the issue of multiple representations and in some of methodologies used to answer research questions. However, it also showed teachers to have different rationales for using representations, to utilize some representations far more frequently than they were present in research base and to treat as default that teachers mediated representations for students whereas research rarely addressed this issue. One of the solutions frequently proposed when considering the research and practice divide is to encourage and value two-way dialogue between the communities. We hope that in identifying where they converge and diverge, we can help make such conversations more fruitful.

Keywords Research • Practice • Teachers • Multi-representational practices • Scientists • Domains • Research-practice gap • SREM • Visual representations • Effectiveness • Learning outcomes • Multimedia • Design • Student learning

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2.1 Introduction

The research reported in this chapter set out explores what researchers and teachers understand about visual representations in science education. It seems evident that both communities place a great deal of importance on such representations. Walk into a typical science classroom and the walls will be covered with pictures, diagrams, maps and graphs; an animation may be projected onto a whiteboard; 3d models will be on desks; textbooks are full of photographs, drawings, charts; and students will be filling their notebooks with a range of multimodal constructions. Similarly, even a quick scan of research literature reveals hundreds of publications every year reporting a variety of studies and theories concerning teaching and learning with pictures, animations, diagrams, multimedia, augmented reality, simulations etc. Such an interest is not unsurprising given the well documented multi-representational practices of professional science and scientists (e.g. Gooding 2004; Kozma et al. 2000; Latour 1999; Lemke 2004) where it is shown that scientists rely on a variety of visual forms to generate new insights and discoveries, explain findings to colleagues and students, and increasingly to excite public interest. If we want students to learn to think like scientists, then it is clear that science education with, about and through visual representations will be crucial.

What is less immediately clear though, is whether the priorities and concerns ("What matters" in Yates's (2004) terms) in teaching and research communities about visual representations are shared equally or whether the different communities have distinctively different issues. We suggest that this question is important, however first we want to argue against a simplistic 'client and customer' interpretation of our question. We are not proposing that researchers should only be permitted (or funded) to research questions of immediate use to classroom teachers. Nor do we propose that teachers should be viewed as passive consumers of research created in Universities. Indeed, the apparently clear differential between teacher and researchers is, of course, questioned daily by the action research practices of teacher-researchers (Cochran-Smith and Lytle 1999; Goswami and Stillman 1987). For example researchers studying for PhDs are often recent or practicing classroom teachers, and teachers are involved in research in a variety of ways as readers, as participants in the studies of others and well as experimenters in their own classrooms (Bates 2002). However, even though the teaching and research communities may have shared membership, it remains the case that "what matters" may differ.

This issue of the relationship between research and practice is clearly fraught and often highly politicised. Consequently, some have attempted to stipulate what makes 'good' educational questions (Hargreaves 1996), others to explore what are appropriate methodologies to answer educational research questions e.g. (Oancea and Furlong 2007; Slavin 2002; Torgerson and Torgerson 2001) and others to identify how best to engage in strengthening the connections between research and practice (e.g. Levin 2013). The goal of this chapter is more humble. We agree with others who suggest that dialogue between members of the communities is a necessary (although far from sufficient) condition for closing a research-practice gap

(Bates 2002; McIntyre 2005). Consequently, we argue that it may be helpful to know what each community talks about. What questions and issues concern researchers? What questions and issues concern teachers? To what extent are these shared issues and to what extent are these distinct concerns of a particular community. In this chapter therefore we attempt to explore "what matters" to whom by exploring the focus within publications in peer-reviewed journals as an indication of research priorities and by interviewing science teachers about their practice with visual representations as well as their views of important research questions and any existing use of research literatures.

2.2 Method

2.2.1 Identifying and Coding the Publications

The research literature was interrogated to answer the question "What are the major foci of published research in the area of teaching and learning with visualisations?" rather than a specific question such as "Do animations help people learn?" or "Do visualization skills predict learning from graphs?" As a result, our search strategy was broad in that we were not aiming to identify relatively few papers to provide direct comparable answer to a specific question as in a systematic review or meta-analysis. It was also broad in that we did not wish limit ourselves to few types of visual representations or particular age range of students. However, it was narrow in that to answer the question of publication and research focus we deliberately chose only journal publication rather seeking grey literatures, conference publication or blogs, etc. We also chose only to look at the last 3 years (2010–2012) as we were interested in the current state of the field and not in how it may have changed over time.

Accordingly the titles of publication in both Educational Resources Information (ERIC) and Web of Science (WoS) were searched with the following word stems: visualisation, visualization, picture, map, diagram, drawing, representation, graph, chart, icon, multimedia. These search terms had been refined through expert consultation. Papers were excluded automatically if they did not refer to peer reviewed published journal papers or were not concerned with educational research. This resulted in an initial set of 898 abstracts. Further exclusions were applied through hand searching these abstracts to exclude papers that were not concerned with primary research (e.g., book reviews, editorials), which used the terms metaphorically (e.g. drawing together, seeing the big picture), where the primary focus was using representations for non-educational purposes (such as knowledge representation in artificial intelligence or pictures in speech therapy) and where representation did not refer to a type of external representation but instead referred solely to mental, political or social representation (such as the under-representation of women in science). Finally, papers were excluded if the domain of study was not Science, Technology, Engineering or Maths (STEM). However, papers that referred to issues that were applicable to STEM domains (such as those described as understanding complex concepts) were included. This initial stage of data reduction resulted in 401 abstracts that were subsequently coded.

We chose to code four aspects of these abstracts – namely the research question or questions under investigation; the representations that were scrutinized in the study; the methods that were employed in the research and disciplinary domain. Appendix summarizes these codes and provides definitions and examples.

The most important code to answer our question concerning the priorities or "what matters" to researchers was to identify the types of research question that the paper was addressing. Consequently, we coded whether the focus on this research was teachers, students, materials or theory and whether the study investigated issues such as learning outcomes, engagement practices, assessment etc. For some issues we have both teacher and student parallels (e.g. student and teacher practices with representations) whereas for others there are only student codes (e.g. representations influence on student learning outcomes or engagement). As many studies explore multiple issues, multiple codes are frequently applied; for example, a study that explored whether students who learned collaboratively rather than individually reported greater motivation and learnt more from an animation than a static picture would be coded as effectiveness, engagement and student practices.

Secondly, we coded the representations that were discussed in the paper. The taxonomy we applied was based upon published taxonomies of representations (Bertin 1983; Lohse et al. 1994) and adapted to include more recently developed representations (e.g. 3d visualizations). We chose to code in relatively broad categories (e.g. graph) rather than more specifically (e.g. line graph, pie chart, box plot). We only coded representations not typically considered as visual (e.g. text, equations but see (Landy and Goldstone 2007)) when they were studied with more traditionally visual forms. One possibly contentious decision has been our choice to distinguish, for some forms of representation, the distinction between construction of the form and interpretation of the form (i.e. drawing/picture; writing/text; talk/narration). These were distinguished because there were sufficient numbers of distinct examples of both uses in the dataset and because research questions were often very different when the study concerned construction rather than interpretation. For example, studies looking at narration were almost invariably concerned with design and effectiveness whereas those that focus on talk normally concerned teacher or student practices. In contrast, other representations such as graph often involved both interpretation and construction in the same study and others still in this dataset were solely used in one way (e.g. interpreting multimedia rather than constructing it). A further concern that should be raised about representation coding is that we typically used the term that the authors used themselves – so it is more than possible that some researchers might have used the term picture where others used diagram to refer to the same representation. Alternatively, people may use the same terms but refer to different representation (for example, it is clear that for some researchers animations mean dynamic depictive representation and count narration as a separate representation whereas other use animation for both). As with research question coding, many studies received multiple instances of this code (e.g. a study could be about diagrams, equations and text).

The third code applied described the research method employed. These were based upon standard categories of methods described in research textbooks (e.g. Cohen et al. 2011; Robson 2011). In general we chose the most specific term appropriate to the study, for example a field experiment that also reported a correlation between a process and an outcome variables as a small aspect of the study would be coded as field experiment whereas the code correlational would applied when the purpose of running the study was to relate two or more variables without an experimental intervention. It was rare for papers to combine multiple studies with distinct research methods (such as a field and a laboratory experiment or an interview followed by correlational study). Nevertheless, such papers were given two codes when they did so. However, in accordance with the definition of case study, which is normally seem as inherently multi-method (Yin 2008), this term was applied if a single study which explored the use of representations in a context was addressed through multiple methods (e.g. survey, interviews, and observations).

The fourth code describes the domains of the study. Standard disciplinary terms were applied (e.g. physics, chemistry, history) rather than specialized areas within these disciplines (e.g. mechanics, optics, thermodynamics). If in the abstract and keywords the domain was only described in general terms as science, engineering, technology then we used these terms. If it was not possible to identify the domain at all we used the term comprehension. Most papers were coded with a single domain but multiple domains would be coded if the research reflected this.

In all these cases, we must acknowledge the limitation of identifying papers from titles and coding them from abstracts and keywords. Papers that referred to visual representations but did not reflect this in the title would not have been selected. Thus, our sample will be an underrepresentation of the number of published papers. Secondly, it must be acknowledged that coding from abstracts and keywords required a degree of inference in multiple cases. Given the large number of papers analyzed in this exercise, it was only practical to code information that was typically available in abstracts. For example, it would have been interesting to code for the age of study participants but as such a large number of papers do not state this in abstract it was not possible to include such a code. Furthermore, abstracts clearly differed in how explicit they were about the details of their study. For example, it may be that many of the papers coded as comprehension were in a specific discipline also coded in our data set but this was not made explicit in the abstract. In summary, given our intent in coding these papers was to identify the focus of research concerned with visual representation and the abstract reveals the authors' view of the most important aspects of their work to highlight, we suggest that these compromises are acceptable. Working within these constraints has allowed us to look much more broadly than would otherwise have been possible. Finally, we do note that as part of our routine professional practice we had in fact read many of the papers that are in the dataset and this clearly would have influenced our interpretation of these abstracts. Thus, it is possible that others would not form the same interpretation from the abstracts as we did.

2.2.2 Interview

Six (2 male and 4 female) science teachers currently working in local (UK) secondary schools were interviewed for this study. They had been teaching for an average of 6.5 years (minimum 2 years and maximum 12 years) and included specific biology, chemistry and physics teachers as well as teachers who taught across the whole science curriculum in their school. One taught only 16–18 year olds whereas the rest taught students from 11 to 18 years.

The semi-structured interviews took around 45 min and consisted of six questions. The structure and content of the interview was inspired by that of Ratcliffe et al. (2004) who focused on teachers' view of research in science education in general but here we modified and adapted to focus specifically on visual representation in science education. Consequently, we asked teachers about how they currently used visual representations; what difficulties students faced in using them; what they would like to know to improve their practice with visual representations and whether they have previously consulted researched to help them; what contributions they thought research with visual representations could make across; and how research could be made more useful for teachers. A card sort presented them with 8 example studies extracted from the dataset above, each presented in a structured template of around 100 words that made clear the research questions, main findings, representations used, topic, methodology employed and context for the study. We chose the cases to ensure a distribution of research questions (as the main priority) but also tried to make sure that topics, research methods and visual representations were also drawn widely. Needless to say, with only eight cases it was not possible to fully counterbalance our selection. Teachers were asked to rank these cases in terms of how useful they or their colleagues would find it and to provide a justification for this ranking. By using a mix of questions that included asking them to recount of their daily practice, questions concerning their view about ideal research and actual examples of research for them to consider, we hoped to gain better insight than if we had simply questioned the teachers about their understanding of the research literature. Following the interviews, each was transcribed and then subjected to thematic analysis by both the authors of this chapter.

2.3 Findings

In this section, we organize the results of these analyses by considering six key findings that emerged from this processes. In each case, we base our discussion on the coded research literature and then consider the issue from the perspectives of the teachers interviewed using illustrative quotes where appropriate.

2.3.1 Visual Representations Are Important in Teaching and Learning Science

In the introduction, we suggested that both researchers in education and science teachers consider visual representations to be an important aspect of science education. This speculation was confirmed by our research. One of the most striking findings to emerge from this exercise is how actively the topic of visual representations in STEM education is researched. We identified 401 journal papers published over 3 years (2010–2012) that had a clear focus on visual representations in STEM education. Moreover, this number is clearly an underestimate of the research activity in this area, as it does not include publications in conferences, books, book chapters or other forms of report. In addition, our selection processes would have excluded papers that did not make a 'representation' in some form or another explicit in their titles. Clearly therefore many researchers consider this to be one of the paramount issues to understand in STEM education. Moreover, the teachers in our study shared this view. All six teachers when asked to recount example of the use of visual representations in their classroom were immediately able to list many examples in their day-to-day practice. Visual representations were commonplace in their classes (e.g. *"almost everything we do involves some form of visual representation"* or *"so many and varied"*). Consequently, it seems that for interviewed teachers that although being asked to explicitly reflect upon the visual representations was an unusual experience, teaching with visual representations was not.

2.3.2 A Diverse Range of Visual Representations Are Important Within STEM Education

The diversity of the research field is reflected in the broad range of visual representations that are studied. We coded 15 different types of visual representations in the research studies and finer grained taxonomy would have identified more than this. For example, we coded diagram rather than its many subtypes (e.g. Venn diagram, circuit diagram, vector diagram, etc.) and graph rather than specific types of graph (e.g. pie chart, histogram, line graph, etc.). All these types of representation may well have distinct benefits for science education as well as potentially facing teachers and learners with distinct problems. Clearly, at whatever level of granularity one chooses to define visual representation (and there is no agreed taxonomy to draw upon) the diversity of representations studied is manifest. Moreover, across the six teachers we interviewed when asked to describe "a few examples from their classroom" 13 of these 15 were mentioned (the exceptions being map and geometry software and it should be noted we did not speak to geography or maths teachers). Note, we did not ask the teachers to list all the representations they used or to recount their teaching practice over extended periods of time, yet no one mentioned fewer than seven distinct types of representation.

2.3.3 Much Learning with Visual Representations Involves Multiple Representations

Altogether 679 representations were identified in the 401 papers. We also coded 50 papers with the code "multimedia" and so by definition those papers also involve multiple representations. Again given the coding decisions described above this will be an underestimation of the frequency of multiple representations. Clearly, therefore a single type of visual representation is rarely used in isolation. However, only 42 papers explicitly referred to "multiple representations" or "multimodal" representations in their title or abstract suggesting that this is more implicit than explicit in many cases.

Teachers also referred to multiple representations either implicitly or explicitly. When describing how they teach a topic, teachers often referenced multiple representations. They talked about using alternative representations at different stages (for example by describing how they would ask students to draw something prior to make a model of it); for different purposes (e.g. "*in a table they cannot pick any patterns but they can from a graph*") or to accommodate different students' preferences ("*some will want to draw things out in pictures or mind, whereas others will choose not to; they prefer to see it written*"). Finally, they also mentioned the intrinsic value of multiple representations for students "*its trying to look at it from different points of view and different perspectives*" whilst being alert to the difficulties that this could bring for students (such as students failing to appreciate that a ball and spring, and a space filling representations were showing the same molecule). All of these issues are key area of concerns within the research literature.

2.3.4 Some Visual Representations Are Seen as More Central in STEM Education Than Others

As can be seen in Fig. 2.1, some representations receive more attention than others. The most frequently coded visual representations in the data set were graph (22 % of papers referred to this form of representation), diagram (also 22 %) and animation (17 %) with text also explicitly mentioned frequently (19 %). This distribution had some parallels with those of the interviewed teachers. The visual representations most frequently referenced by the teachers were diagrams and animations as all six mentioned these forms when asked to list visual representations they used. Five of the teachers also referenced pictures. However, only three teachers mentioned graphs suggesting that either teachers focus less on graphs in the classrooms that the research literature or that teachers do not immediately think of graphs when asked to reflect on visual representations.

However, the teachers (4 from 6) made much more reference to photos and videos than the coded research literature as only 2 % of papers were coded as referring to photographs and 3 % to video. Four teachers also mentioned modeling (4 %)

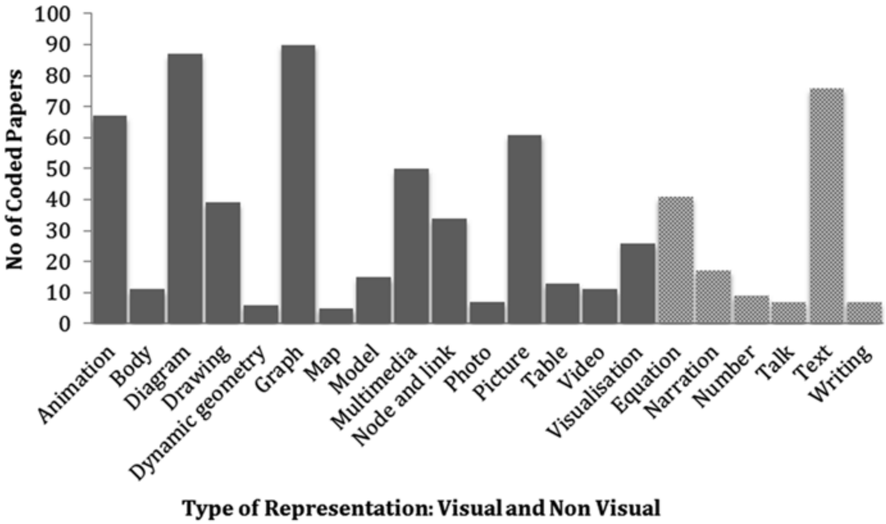

Fig. 2.1 Types of representations coded in the data set

and drawing (10 %) which relatively speaking seems to suggest that these representations loom larger in teachers' minds that in the research literature.

2.3.5 There Are a Range of Important Questions to Be Answered Concerned with Teaching and Learning with Representations

The research papers in this dataset addressed a diverse range of issues as can be seen in Fig. 2.2 However, it is clear that the issue of effectiveness (is representation X more effective than representation Y for improving student learning outcomes) predominate as 31 % of papers were primarily concerned with this issue. These papers are similar in style and focus to papers coded as design that concern whether representations should be designed in particular ways (e.g. segmentation of animations or learner control of video) to enhance their effectiveness (13 %). Evidently, the majority of research is concerned with how the design and choice of representations influences students' learning outcomes. However, relatively few papers addressed the teacher's role when considering visual representations in STEM education (8 %) suggesting the majority of papers did not see a role for the teachers in mediating the ways that representations influence student learning. Other questions which had little presence in the coded dataset were papers which addressed on how representation are used for assessment (5 %) and those which focussed specifically on theory building (2 %) (proposing new theoretical approaches or specifically setting out to test predictions of a theory rather than applying a theory to understand results).

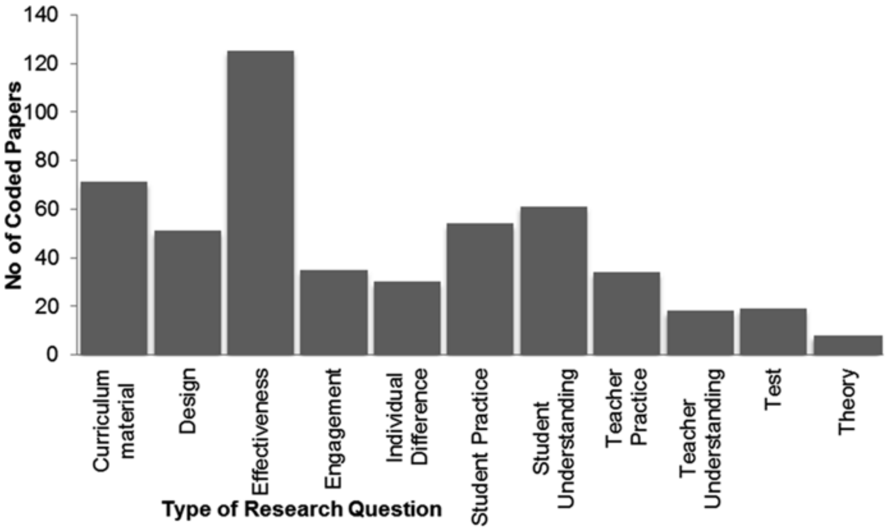

Fig. 2.2 Frequency of research questions coded in the dataset

In terms of what teachers saw as important questions to be concerned with – 'what matters' in Yates' (2006) terms, four of the interviewed teachers' priorities when directly questioned were also concerned with effectiveness of different forms of representations (e.g. *"whether using a certain types of visual representation would improve their (student) learning"*) or how representations should be designed to most enhance student learning (e.g. when talking about the complexity of information shown in a representation *"whether it would better to go more simply or more complex and dial it down a little bit"*). In the research literature (e.g. Vanderlinde and van Braak 2009), one often cited reason for the gap between educational research and practice is the view that teachers are focused on finding out "what works" and educational research is therefore of too little practical relevance. Bates (2002) has argued that teachers tend to want solutions to problems whereas the researcher seeks new knowledge. In this specific research area, however there seems to be general alignment between the new knowledge sought by researchers and the questions that the interviewed teachers consider important.

However, this does not mean that all teachers felt that the research literature would be the obvious place to turn for answers to these questions. Two interviewees questioned whether studies would be necessary to tell them this suggesting "*But that then is where your professional judgment as a teacher comes in, to figure out what is appropriate for the student sitting in front of you*" arguing that their experience as classroom teachers has provided them with many opportunities to assess when a representation was effective for their students. In addition, some raised doubts as to whether the sorts of answers found in the literature would be helpful for them. One questioned whether research concerning students from outside the UK would be helpful *"there is a cultural way that students are going to approach their* *learning and also differences how they might be examined as well"* and another raised the issue of generalization overall *"Because it will always be different for different students"*.

The other teacher who saw an immediate and strong rationale for research focused particularly on misconceptions and wanted to know more about the difficulties that representations can bring in addition to their benefits. In the dataset 15 % of the papers described student understanding or more commonly misunderstandings of a type of representation (e.g. the difficulties students experienced in understanding graphs of motion). Consequently, it also seems for this teacher that the research base can provide an answer to questions that interest her, but as we argue below this conclusions needs to be considered in reference to the type of representations as well as the research questions.

As part of the interview, we had provided teachers with the eight examples from the dataset to be ranked in terms of what they thought were would be useful. This task also revealed their interest in the design and effectiveness of representations. The paper ranked as most useful overall concerned the effectiveness of different forms of representation for teaching chemistry. All teachers ranked this in the top half of the cases, often making reference to it usefulness and relevance to their practice as well as their view it had a strong research design (see below). The (joint) second highest-ranking paper concerned design of multimedia and pace of instruction. Teachers typically also considered this a strong study with one considering it a model of what he wanted the research literature to look like. However, some teachers questioned its value for them as teachers arguing it was more suitable for animation developers and another that it did not have a specific lesson objective. Interestingly, the teachers who did rank it highly considered how they could adapt and apply its findings to situations over which they did have control (such as how they could talk or not over an animation in a PowerPoint presentation).

In terms of what the six teachers considered less useful, a paper describing textbook design and how it has changed over time was almost universally judged as uninteresting. Rationales for placing this as least useful were that it did not address whether some designs were more effective than others, did not tell them anything surprising ("*its just common sense*") but also for two teachers they no longer (or rarely) used commercially published textbooks preferring to develop their own materials. Two further papers ranked almost equally low but for very different reasons. The first focused on whether teachers understood a topic and could draw it; and here the rationale for ranking low concerned how this paper would directly help them teach their students as well as sympathy for the tested teachers. The second was an extended case study of a single student learning physics in a representationally rich sequence of lessons. The rationale provided for ranking this paper lower often rested on the interviewed teachers concerns about the methodology of the research (see below). This case was also most representative of the type of study we coded as curriculum material (17 %) in the dataset. These studies typically describe a proposed novel representation or lesson plan involving a representation without providing much in the way of evidence of their use in classrooms either in terms of student practices or outcomes. These sorts of studies are particularly frequent in disciplinary journals often aimed at teaching professionals as much as researchers. Our teachers' responses suggest they would place only limited value on such accounts.

Two of the cases to be ranked addressed how teachers' practices can support student learning; one a more focused case study based on interview and lesson observation of a small number of teachers and the second a large survey of 100s of students and their teachers. These papers were almost identically ranked at the centre of distribution. However, these studies provoked with widest variation in teachers' responses. Some argued they were beneficial as they revealed the roles that teachers could play, but others felt that they added nothing new to their knowledge as practioner as they already supported student learning in the ways that the paper describe.

There were two significant issues for teachers, mentioned by all six interviewees, which do have relatively low coverage in the research literature: (a) the ways that representations can shape engagement and motivation and (b) individual differences in student learning with representations.

All six teachers were clear about how important it was that representations interested students and for many, it was the most important reason for them to select a representation. Their understanding of student interest was nuanced – they spoke about the importance of not over using forms of representation which might seem superficially likely to engage (such as video) or simply entertain without strong educational purpose. In contrast, engagement is raised in the research literature, but it does not receive strong attention as it was addressed by only 9 % of the coded research paper.

The other factor that was common to all the interviewed teachers was their interest in individual differences and whether learners with different epistemological beliefs, with different prior knowledge or different abilities would respond to representations differently or require differentiated teaching. This was not a strong focus of research with only 6 % of papers coded examining how individual differences between students influenced their learning.

Finally, teachers also raised a host of other issues in their general discussion and which show in many instances strong overlap between the concerns of the two communities. For example, teachers discussed their worries about how pictures were often simply used to decorate textbooks rather being functional – linking with the research communities interest in the functional roles of pictures (Levin et al. 1987) and whether this leads to seductive details effects (Harp and Mayer 1998). They wondered when more realistic images were more helpful than abstract ones (e.g. Scheiter et al. 2009). They also mentioned the value in knowing how to help students become independent learners able to regulate their own learning with representations (e.g. Azevedo and Cromley 2004). They spoke about visual representations being useful when they made visible for students things that would otherwise be impossible to show in the school classroom because they are invisible without specialized equipment or at timescales not possible to experience, (e.g. Olympiou et al. 2012). Finally, they often spoke of issues only just becoming topical in the research literature such as the value for students in drawing their own understanding (Ainsworth et al. Tytler 2011), the value of a representationally rich curriculum (Hubber et al. 2010) embodiment (Hostetter and Alibali 2008) or in how to "flip" their classroom (Goodwin and Miller 2013) by using social media to present students with animations or videos to be discussed in class later.

2.3.6 Certain Research Questions Are More Often Associated with Particular Forms of Representations

It is clear from the coding that certain research questions were differentially associated with different forms of representation. For example, effectiveness and design questions were coded in 43 % of the papers making the issue by far the most frequently researched. These issues were frequently associated with animation (81 % of paper coded with animation addressed these questions) and multimedia (74 %) but much less, for example, with graphs (15 %). However, graphs were the most frequently studied representation when addressing student understanding (25 %) whereas animations (4 %) and multimedia (3 %) barely featured. It is not clear why there should be such disparity between representations. One possibility is that as research with a representation matures the field moves from what Goldman (2003) calls first generation research (typically "is this representation effective?") to second-generation questions, which address issues such as who benefits from learning with (specific forms of) representation? How do they learn and how does this change over time and how does the wider context influence learning with representations (Ainsworth 2008). As representations such as animation, 3d visualizations and multimedia have only recently become technically possible, research may be more likely to be first generation in style whilst representations such as graphs (which in many forms have been available for centuries) could be expected to be associated with a wider range of issues. One lesson that could be learnt if this is the correct explanation is that research that has looked for simple "first generation" answers to effectiveness questions has not typically found them to apply. Consequently, it may be more appropriate to raise a wider range of issues earlier in researching new forms of representation.

We did not ask teachers specifically about whether there were some issues that were more important for them with particular representations. However we did note that in common with the research literature they also focused on the difficulties students have with graphs. Other issues raised by the teachers that have also be discussed in the research literature include the difficulties of relating 2d and 3d (Huk et al. 2010) representations, representing invisible objects (Wu et al. 2001), students be able to distinguish conventional aspects of the representation from those which have more intended meaning (Hubber et al. 2010) and the problems of helping children understand representations which do not accord to their own mental representations of the phenomena.

We now turn briefly to the final codes we applied to the dataset, methodology and topic (Fig. 2.3).

The three most common methods in the dataset were case study (23 % of the papers used this method), field experiment (19 %) and lab experiment (16 %). As would be expected, certain research questions were differentially associated with these methods: 75 % of design and effectiveness questions were answered using experimental methods whereas 55 % of studies concerning teacher or students practices used case study methods. Perhaps the only surprise is the infrequency of papers in the coded dataset that included multiple methodologies. Although case studies

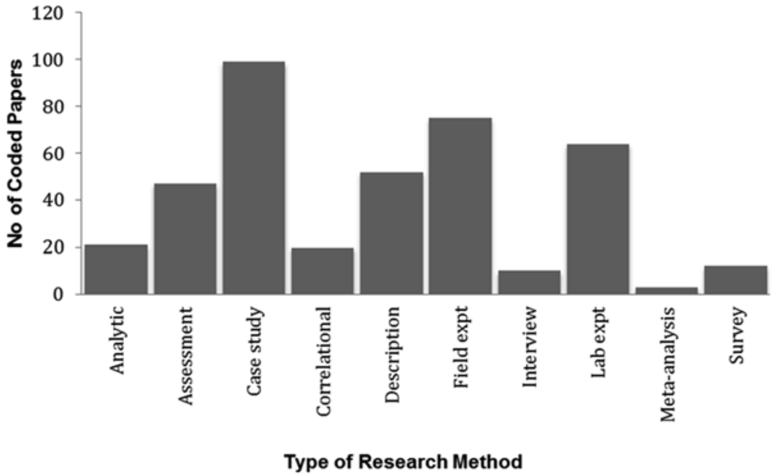

Fig. 2.3 Frequency of research methods coded in the data set

were frequent (which could include multiple methods of data collection with a single study), only two papers were coded as using multiple methods, which meant they included at least two separate studies that used different methods for different studies (e.g. a lab experiment followed by a field experiment or an interview with teachers followed by case study of classroom practice). This is perhaps a concern given the increasing recognition that multiple methods can offer distinct benefits for addressing educational questions (Johnson and Onwuegbuzie 2004).

In terms of teachers' views of methods, others have noted (Ratcliffe et al. 2004) that science teachers have a preference for experimental methods in judging research quality. We did not specifically focus on this issue in the interviews. However, three of teachers did explicitly mention methodological criteria when justifying their ranking of the presented and tended to see experimental methods (whether laboratory or field) with larger number of participants as preferable to smaller more detailed case studies. They were all clear that they wanted evidence and so the method we coded as description, which was typically associated with the development of curriculum materials and reported an innovation without evidence concerning its effectiveness, engagement or impact on student practices or understanding, was not considered of particular value (Fig. 2.4).

Finally, we report the domains that we identified in the dataset. It is clear that the issue of visual representation is of interest widely across the STEM disciplines. However, there are predictable domain specific differences in the types of representations associated with each domain. For example, physics and chemistry were both coded 42 times in the dataset. Graphs were more frequently studied in physics (40 % of paper coded in physics concerned graphs) than chemistry (10 %) and animations (23 %) more frequently in chemistry than physics (10 %) whereas both domains discuss diagrams and equations with roughly equal frequency.

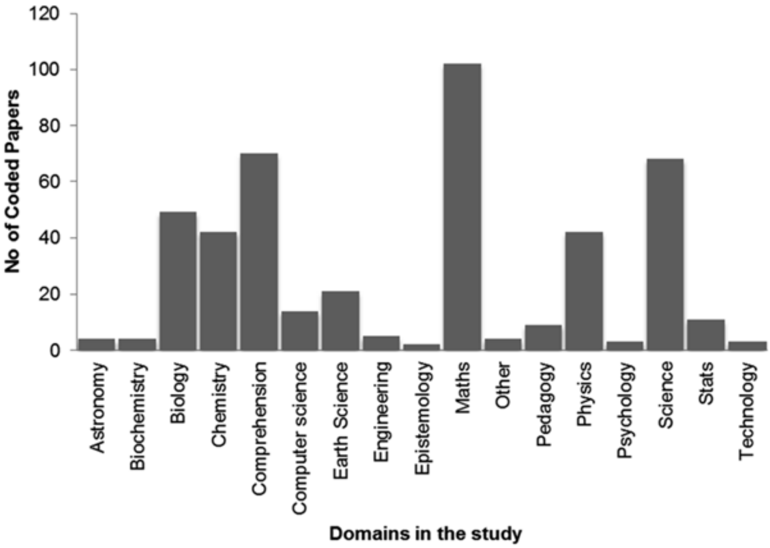

Fig. 2.4 Frequency of domains coded in the data set

We had deliberately sought teachers across the range of science disciplines to interview (although we must note the lack of maths teachers) in order to limit sampling bias. However, as with the research literature there was equal interest in visual representation from the teachers of all topics, with again predictable domain specific interest (for example, a biology teacher was concerned with fidelity of representation whereas the a chemistry teacher was concerned with how students related 2d pictures in textbooks to 3d models in their hands). In terms of what teachers felt was most interesting or useful for the research, we observed no strong disciplinary differences with our interviewed teachers able to put themselves into their colleagues shoes when necessary (for example, physics teachers as well as chemistry teachers ranked the paper on 3d stereochemistry representations as most useful). Nonetheless, our teachers commonly taught across a range of science topics as well as their own specialty so it may be the case that teachers of single subjects would have made different decisions.

2.4 Discussion

The relationship between research and practice has been highly controversial for many years and remains so. Many see a huge gap between research and practice (Hargreaves 1996) although others point out that research influences practice in a variety of ways which can be indirect and subtle (Bates 2002; Yates 2004). One reason that if often cited for this gap is a difference between the priorities of researchers and research, and the priorities of teaching and teachers. Consequently, we set out to explore in the very specific domain of visual representation in science education the extent of the differences and overlap between the two communities views of “what matters”. We did this by coding a significant proportion of the research literature and interviewing a sample of practicing science teachers.

Our research suggests that a general level there is strong alignment between these two communities. Both communities consider visual representation to be fundamentally intertwined with science education. In terms of the strong presence in the research literature and frequency of use in the science classroom, it is clear there is a strong basis for conversation. Visual representations were researched across a wide range of STEM disciplines and the teachers in our study came from biology, chemistry and physics backgrounds. More specifically, researchers in this area share with teachers a strong interest in the effectiveness of a particular design of visual representation for teaching a particular topic. To some extent this is surprising, as much has been written about the gap between teachers who wish to find out “what works” and researchers who do not attempt to address this question (e.g. Vanderlinde and van Braak 2009). In this area at least the priorities of the two communities align, although we personally share the belief of others (e.g. Goldman 2003) that in fact the answers to this question are more complex than either community may desire. Further commonalties can be seen in the emphasis on multiple representations, and the tendency of researchers in this area to use experimental methods. Finally, some of the most frequently studied representations (animations, diagrams) also seem to be the ones that the teachers most frequently used.

There were however some differences in the two communities’ priorities. Teachers in our study frequently talked about using representations that have received relatively little attention in the research literature – at least between 2010 and 2012– most notably photographs and video but also the use of models and student drawing. They also were concerned with issues that did not receive much attention such as individual differences and engagement. Another key difference between the communities is in the role of teachers in supporting student learning from representations. Only 8 % of the papers addressed these issues but for the teachers we spoke to, it was clear that their professional practice involved constant mediation between the students and the visual representations with which the students were working.

The major question that arises from having identified the gaps between research and practice, what if anything, should be done to fill them? One frequent suggestion is that researchers should pay more attention to the issues that face teachers and turn their attention more often to issues such as engagement or teacher mediation or representations such as photographs. Although, we would not want to argue that all research should be led by classroom teachers’ preferences, many researchers may welcome the opportunity to explore issues of more immediate practical benefit. Moreover, the value for research of seeking to formalize and theorize practice and craft knowledge, and in the consequence, the two-way nature of the dialogue between classroom and university is now recognized in general (McIntyre 2005). However, it is not clear how much this has influenced research with visual representations.

Another solution is that teachers should be made more aware of the research findings and adapt their practice accordingly. The problems with this solution are well documented (e.g. Williams and Coles 2007; Levin 2013; Ratcliffe et al. 2004). For example, teachers face a multitude issues in their day-to-day practice, clearly they cannot consult the literature about everything; even if that literature was relevant, easy to find, free to use and written accessibly (and clearly in many cases none of this will be true). Consequently, the teachers in our study (and those of others, Ratcliffe et al. 2004) valued dissemination through membership of professional associations, from peers and senior leaders in their schools, professional development, indirectly through resource provision ("good biology diagrams are so hard to find") and increasingly through social media such as Twitter (e.g. Donmez et al. 2012).

Moreover, as many of our teachers articulated, the importance of personal and professional judgment acquired through experience will often remain more important than researchers' findings when it comes to changing and adapting their practice. Their views of themselves as teacher-researchers accords here with many others (e.g. Goswami and Stillman 1987). Published research filters into these activities more tacitly and through changing conceptual structures rather than in specific findings. However, not all the teachers valued this approach and would not consider that their own actions to improve their teaching as research. Consequently, a diversity of approaches to filling the gap remains appropriate (McIntyre 2005).

In conclusion, we must mention the limitations of the research and how we intend to take it forward. Clearly the main limitation of the study is that only six teachers were interviewed and many of them were alumni of the University of Nottingham where teacher education explicitly addresses the value of practioner inquiry. Consequently, we need to expand our sample of teachers to include those from a more diverse background and with differing experiences of research. As we include papers in the area of mathematics within our coded data set, then seeking the views of mathematics teachers would be opportune. It would also be desirable to code a portion of the dataset from full papers to identify how much our decision to code from abstract and keywords has influenced our conclusions about their content as well as seek inter-rater reliability checks with those who have not read the papers. Furthermore, there were many issues in the dataset and interviews that we had not covered in this initial report of our research. Finally, by undertaking this exercise we have reawakened our desire to participate in the dialogues whose value we have articulated and to continue to contribute to the development of a shared vision for research and teaching with visual representations in science education.

Acknowledgements We are very grateful to the teachers who agreed to participate in this study and to the editors who allowed us to be so late in submitting this chapter.

Appendix: Coding Rubric

Code	Definition
	Research question
Curriculum material	Discusses a lesson plan, an innovative piece of software, analysis of a textbook etc. Does not report student or teachers use of it, responses to it, etc
Design	Examines a design choice within a representational format; for example segmentation of an animation or sequenced or simultaneous text or pictures
Effectiveness	Is a representation effective at teaching something; e.g. do animations help student understand the cardio-vascular system
Engagement	Is a representation engaging? What are learners affective responses to the representations?
Individual difference	Individual differences (gender, expertise, spatial ability etc) in students learning with representations or with teachers teaching with representations
Student practices	This codes refers to what do students do with a representation and also if students have been directed to perform a particular practice; for example, how students coordinate representations or asking learners to self explain a picture.
Student understanding	Explores what students understand or misunderstand about a topic or representation
Teacher practices	What do teachers do with a representation?
Teacher understanding	Explores what teachers understand or misunderstand about a topic or representation
Test	Explores the way that a representation can be used as an assessment; for example; how useful are concepts maps for assessing student understanding of a topic
Theory	Research which specially tests, refines or develops a theory of learning or teaching with representations but not one which simply uses a theory to help explain other research.
	Representation
Animation	A dynamic representation which is pictorial
Body	Gesture or whole body enactment and haptic representations
Diagram	A 2d graphical representation which relies on some abstraction
Drawing	Self generated graphical representations
Dynamic geometry	Specific geometry software
Equation	Any kind of symbolic formula include maths and chemistry
Graph	Any type of graph, line graph, bar chart, pie chart etc
Map	Geographical map
Model	Physical 3d model not digital also using for manipulative
Multimedia	This term is used when the system is described as multimedia without further specification such as animation + narration.
Node and link	Any type of node and link representation (e.g. argumentation map, mind map, concept map)
Number	Numbers in digit form
Photo	Photorealistic picture
Picture	Depictive graphical representation (not self generated)
Narration	Spoken text provided by software not spoken by learners
Table	All tabular representation

(continued)

Code	Definition
Talk	Talk by learners
Text	Written text presented to students
Video	Dynamic visualisation that is photorealistic
Visualisation software	Digital visualisation not of the specific types already coded
Write	Written text constructed by student
	Method
Analytic	Expert analysis of an representational practice using a specified approach (e.g. semiotic analysis)
Assessment	A method based primarily of getting people to answer questions, perform a task (and can include interviewing people as they perform the task)
Case study	Explores activity in a context and can include a range of methods
Correlational	Relates two or more variables collected by survey; experiments which reports correlation between process and outcome variables are not coded as correlational
Description	A description of representation or pedagogy which is likely to be intuitive
Field expt.	Experiment in a field context and could include quasi-experiments
Interview	A method based primarily of getting verbal responses to questions without specific emphasis on performing tasks
Lab expt.	Experiment an artificial context but could include a school setting if it used a lab approach (e.g. not a normal class, students random assignment, learning something not in their course)
Meta-analysis	Statistical process to combine findings from different studies
Survey	Surveys students or teachers, not case study as no real description of context; not correlational as not related to other measures
	Domain
Astronomy	Study of celestial objects
Biochemistry	Chemical processes in biological organisms
Biology	Study of life and living organisms
Chemistry	Study of the composition, properties and behavior of matter
Comprehension	When domain is not specified (e.g. reading a complex text)
Computer science	Approaches to computation includes programming
Earth science	A broad category for understanding the earth
Engineering	A broad category for all topics related to understanding machines and structures when no specific information is provided
Epistemology	Refers to teachers or students beliefs about knowledge
Maths	A board term for all mathematical topics including algebra, geometry, calculus etc
Other	Topics such as history, English etc when included in a paper which was also about STEM disciplines
Pedagogy	When the topic represented was pedagogy rather than the focus of research question
Physics	Understanding such concepts as matter, force, space and time
Psychology	Refers to human mental function and behaviour
Science	When the domain is just described as science
Stats	Study of the organization, analysis, interpretation, and presentation of data
Technology	Used when the topic is technology without specific information

References

Ainsworth, S. (2008). How should we evaluate multimedia learning environments. In J.-F. Rouet, R. Lowe, & W. Schnotz (Eds.), *Understanding multimedia comprehension*. New York: Springer. ISBN 978-0-387-73336-4.

Ainsworth, S., Prain, V., & Tytler, R. (2011). Drawing to learn in science. *Science, 333*(6046), 1096–1097. doi:10.1126/science.1204153.

Azevedo, R., & Cromley, J. G. (2004). Does training on self-regulated learning facilitate students' learning with hypermedia? *Journal of Educational Psychology, 96*(3), 523–535.

Bates, R. (2002). The impact of educational research: Alternative methodologies and conclusions*. *Research Papers in Education, 17*(4), 403–408. doi:10.1080/0267152022000031379.

Bertin, J. (1983). *Semiology of graphics: diagrams, networks, maps* (W. J. Berg, Trans.). Madison: University of Madison Press.

Cochran-Smith, M., & Lytle, S. L. (1999). The teacher research movement: A decade later. *Educational Researcher, 28*(7), 15–25.

Cohen, L., Manion, L., & Morrison, K. (2011). *Research methods in education*. Oxford: Routledge.

Donmez, F. I., Odabasi, H. F., & Erol, O. (2012). *Twitter for collaborative professional development.* Paper presented at the Society for Information Technology & Teacher Education International Conference. Austin, Texas, USA.

Goldman, S. R. (2003). Learning in complex domains: When and why do multiple representations help? *Learning and Instruction, 13*(2), 239–244.

Gooding, D. C. (2004). Cognition, construction and culture: Visual theories in the sciences. *Journal of Cognition and Culture, 4*((3–4)), 551–593.

Goodwin, B., & Miller, K. (2013). Evidence on flipped classrooms is still coming in. *Educational Leadership, 70*(6), 78–80.

Goswami, D., & Stillman, P. R. (1987). *Reclaiming the classroom: Teacher research as an agency for change*. Upper Montclair: Boynton/Cook.

Hargreaves, D. H. (1996). *Teaching as a research-based profession: Possibilities and prospects*. Teacher Training Agency Annual Lecture, London.

Harp, S. F., & Mayer, R. E. (1998). How seductive details do their damage: A theory of cognitive interest in science learning. *Journal of Educational Psychology, 90*(3), 414–434.

Hostetter, A., & Alibali, M. (2008). Visible embodiment: Gestures as simulated action. *Psychonomic Bulletin & Review, 15*(3), 495–514. doi:10.3758/pbr.15.3.495.

Hubber, P., Tytler, R., & Haslam, F. (2010). Teaching and learning about force with a representational focus: Pedagogy and teacher change. *Research in Science Education, 40*(1), 5–28.

Huk, T., Steinke, M., & Floto, C. (2010). The educational value of visual cues and 3D-representational format in a computer animation under restricted and realistic conditions. *Instructional Science: An International Journal of the Learning Sciences, 38*(5), 455–469.

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Researcher, 33*(7), 14–26. doi:10.3102/0013189x033007014.

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. *Journal of the Learning Sciences, 9*(2), 105–143.

Landy, D., & Goldstone, R. L. (2007). Formal notations are diagrams: Evidence from a production task. *Memory & Cognition, 35*(8), 2033–2040.

Latour, B. (1999). *Pandora's hope: Essays on the reality of science studies*. Cambridge, MA: Harvard University Press.

Lemke, J. L. (2004). The literacies of science. In E. W. Saul (Ed.), *Crossing borders in literacy and science instruction: Perspectives on theory and practice* (pp. 33–47). Newark: International Reading Association.

Levin, B. (2013). To know is not enough: Research knowledge and its use. *Review of Education, 1*(1), 2–31. doi:10.1002/rev3.3001.

Levin, J. R., Anglin, G. J., & Carney, R. N. (1987). On empirically validating functions of pictures in prose. In D. M. Willows & H. A. Houghton (Eds.), *The psychology of illustration: I. Basic research* (pp. 51–85). New York: Springer.

Lohse, G. L., Biolsi, K., Walker, N., & Rueler, H. (1994). A classification of visual representations. *Communications of the A.C.M, 37*(12), 36–49.

McIntyre, D. (2005). Bridging the gap between research and practice. *Cambridge Journal of Education, 35*(3), 357–382. doi:10.1080/03057640500319065.

Oancea, A., & Furlong, J. (2007). Expressions of excellence and the assessment of applied and practice-based research. *Research Papers in Education, 22*(2), 119–137. doi:10.1080/02671520701296056.

Olympiou, G., Zacharias, Z., & deJong, T. (2012). Making the invisible visible: Enhancing students' conceptual understanding by introducing representations of abstract objects in a simulation. *Instructional Science, 41*, 1–22.

Ratcliffe, M., Bartholomew, H., Hind, A., Leach, J., Millar, R., & Osborne, J. (2004). *Science education practitioners' views of research and its influence on their practice*. York: Department of Educational Studies, University of York.

Robson, C. (2011). *Real world research: A resource for users of social research methods in applied settings*. Chichester: Wiley.

Scheiter, K., Gerjets, P., Huk, T., Imhof, B., & Kammerer, Y. (2009). The effects of realism in learning with dynamic visualizations. *Learning and Instruction, 19*(6), 481–494. doi: http://dx.doi.org/10.1016/j.learninstruc.2008.08.001

Slavin, R. E. (2002). Evidence-based education policies: Transforming educational practice and research. *Educational Researcher, 31*(7), 15–21. doi:10.3102/0013189x031007015.

Torgerson, C. J., & Torgerson, D. J. (2001). The need for randomised controlled trials in educational research. *British Journal of Educational Studies, 49*(3), 316–328.

Vanderlinde, R., & van Braak, J. (2009). The gap between educational research and practice: Views of teachers, school leaders, intermediaries and researchers. *British Educational Research Journal, 36*(2), 299–316. doi:10.1080/01411920902919257.

Williams, D., & Coles, L. (2007). Teachers' approaches to finding and using research evidence: An information literacy perspective. *Educational Research, 49*(2), 185–206. doi:10.1080/00131880701369719.

Wu, H. K., Krajcik, J. S., & 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. doi:10.1002/tea.1033.

Yates, L. (2004). *What does good education research look like?: Situating a field and its practices*. Maidenhead: McGraw-Hill International.

Yin, R. K. (2008). *Case study research: Design and methods* (Vol. 5). Thousand Oaks: Sage Publications.

Part II
Teachers' Selections, Construction, and Use of Visual Representations

1.1 Introduction

This part, which consists of four chapters, is concerned with how teachers go about the three processes of creating their own representations, of selecting existing available representations, and then of using those that they consider of greatest value.

In the first paper, Eilam Poyas and Hasimshoni (this volume, Chap. 3) directly tackle the first two issues. Seventy-five science and mathematics teachers with a wide range of professional experience were given three tasks. In the first, they were provided with the texts of three contrasting scenarios and asked to generate a representation that best depicted each of them. In the second, they were then given four representations that varied in terms of type, accuracy of depiction, and sophistication of depiction, for each of the three scenarios, and asked to choose the most suitable in multiple choice questions. In the third, they were asked to give the reasons, verbally and in writing, underlying their choices in the two earlier tasks.

The results showed a heavy dependence of the language used in the tasks for the decisions made. This immediately has implications for the linguistic/cultural compatibility of teacher and students, a theme that is taken up in Part III. The teachers found the wording of the captions for representations difficult to produce, which may have implications for students' evaluation of those depictions. The teachers tended to opt for the simpler types of representation, especially when these were highly valued in their parent discipline, but even then did not exploit the full potential of the system chosen. The implications of this paper are that visualisation must be included in both pre- and in-service education if teachers are both to avoid the culturally-oriented 'linguistic traps' that await the unwary and to make the best use of the specific types of representation that they select.

The second paper, by Loughran (this volume, Chap. 4), presents an approach to teaching with visualisations that addresses both the above issues, albeit indirectly, whilst representations are created. A 'slowmation' is a low-tech form of animation that can be readily developed both by teachers and by students. The slowing-down of an animated diagram sequence enables the producer and the user to 'unchunk' the knowledge involved in the information being presented. This slowing down of information enables the user to more clearly understand the individual concepts being represented by, in effect, turning abstract ideas into a concrete form, thus making them more mentally accessible. Developing slowmations in teacher education causes those involved to think both about their own understanding of the ideas being presented and about how they would use the approach with students. When done with students, the approach offers a good opportunity to grasp the nature of existing misconceptions and to avoid the creation of new ones, it is claimed. Both the language used and the conventions associated with particular forms can be highlighted in the creation and use of slowmations, which should have a clear role both in teacher education and classroom practice.

The third paper, by Liu Won and Treagust (this volume, Chap. 5), looks at the use of existing representations in one particular teaching context: that of biology classes given by five teachers to 120 Grade 8–12 students over a 7 month period. Most helpfully for the reader, the work is presented with the use of three assertions about what was observed to happen, all illustrated from the data collected in the inquiry. The first assertion, that teachers use diagrams not only to represent the schematic relationship between the different concepts involved but also to teach the nature of these concepts, neatly illustrates the flexibility and representation power of the diagrams genre. The second assertion is that teachers use different diagrams interchangeably as they forge links between students' knowledge of a topic at the macro, sub-micro, and symbolic, levels. Given that such linkages are vital if students are to be able to fully understand a particular concept, the intellectual power of diagrams is again reinforced. The third assertion, that teachers' use of diagrams involves their use of verbal analogies, often prepared in advance, to support students' understand of those diagrams, is intriguing in that its success depending on the students' understanding both the nature of analogy itself and of the sources from which they were constructed. Again, linguistic and cultural issues come to the fore.

The fourth paper, by Cheng and Gilbert (this volume, Chap. 6), is also concerned with the use of representations to depict a phenomenon at each of the three levels of representation – macro, sub-micro, and symbolic, and the relationship between them. The phenomenon is that of stoichiometry, the quantitative relation between the reactants and the products in a chemical reaction, a nested set of concepts that pose great challenges to students of chemistry everywhere. The problems that students have in understanding the representation of each of the three levels are reviewed as is good practice in the teaching of each. These three sets of data are then orchestrated into an overall scheme and an account given of its use with a Grade 10 class. Again, the emphasis is on the invaluable part that representations play in the teaching of sections of a thematic field and in the bringing together of these sections into a whole that transcends the individual components.

The conclusion that can be drawn from this part is that teachers' selection of representation, their construction of suitable representations, and their use with students, are of vital components of science education. This implies that these processes should form part of science teacher education. However, in Part IV, we show how such teacher education is bound to be a complex issue.

Chapter 3
Representing Visually: What Teachers Know and What They Prefer

Billie Eilam, Yael Poyas, and Rachel Hashimshoni

Abstract Visual representations (VRs) are perceived as crucial to science learning and teaching. Despite teachers' central role in mediating between information (including visual information) and learners, teachers' knowledge in the domain of information representation has received only limited attention. We aimed to examine aspects of VR knowledge and competence among 72 science and math teachers from diverse backgrounds, by investigating teachers' self-generated VRs and preferred ready VRs to represent textual data. First, teachers were asked to self-generate a VR to accurately represent each of three given textual scenarios of different types. Next, in a multiple-choice task, teachers were asked to select the single VR that most efficiently represented each of these same three textual scenarios, from a set of four ready VRs per scenario. Teachers could select a VR type that resembled or differed from the type they had self-generated. Participants then reasoned about their self-generated products and their choices of ready VRs – in writing and in interviews. Content analysis was performed on the self-generated and the selected ready representations and on teachers' written and transcribed interview responses. Findings revealed the impact of teachers' lack of training in this area on their performance and products.

Keywords Visual representations • Self-generated representations • Selection of representations • Teachers' knowledge • Culture • Multimedia • Language as communication • Teachers' visualization and competence

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Science and math teachers hold the main responsibility for mediating between contemporary scientific information and students' learning of that information. To fulfill this role in the face of today's VR-rich learning materials, teachers must possess sufficient knowledge about the different characteristics and unique properties of diverse information representation types and, particularly, about VRs; namely, teachers should be "visually literate" (Eilam 2012). This chapter will examine teachers' performance while generating their own VRs and while selecting the preferred VRs from given options to represent textual data. In this chapter, we will discuss teachers' preferences for self-generated and selected VRs and will attempt to link our findings with specific issues that may hold implications for teacher education. VRs in this chapter are defined after Ainsworth and Lowe's (2012) as an indirect or "secondhand" account of a subject or a topic that encapsulates selected aspects of it.

As described above, the little existing literature about teacher visualization frequently pertains to the pedagogies that teachers apply using VRs (e.g., the use of different types of VRs in the instruction of different types of relevant knowledge), rather than to their knowledge and understanding of visualization per se. Therefore, in the current chapter we investigated science and math teachers' knowledge of representing and VRs, which has been the outcome of a long-term formal and informal knowledge construction, in an attempt to reveal their representational competence. However, such an investigation is not a straightforward task, as discussed next.

3.1 Difficulties in Studying Teachers' Knowledge

Teachers' knowledge of a domain influences their teaching, choices, and practices (Loughran et al. 2004). As a complex internal construct (Baxter and Lederman 1999), knowledge can only be uncovered by eliciting teachers' articulation of it and by examining their performance on well-designed relevant tasks. These two modes are complementary in the sense that each provides insights into different aspects of knowledge and each has its limitations. For example, teachers demonstrate difficulties in articulating their knowledge because it is often tacit and beyond teachers' awareness or because it is highly contextualized and situative (Kagan 1990; Korthagen and Kessels 1999; Schön 1983). In addition, research on learning with multimedia has shown that protocols of verbal descriptions regarding representational usages tend to produce incomplete data and only reflect participants' conscious use of representations. Thus, complementary performance-based methods are required for characterizing teachers' representational competence (Steiff et al. 2011).

Hence, we attempted to uncover what teachers know about representing and about visualization on the basis of both what they say and what they do. We designed a study that included both specifically designed performance tasks and in-depth interviews. These enabled us to complementarily investigate both teachers' representational behavioral choices and their written and verbal self-reflections articulating their knowledge of the topic. Because only a few studies have been reported about teachers' performance and knowledge of representations, this qualitative paradigm is more suitable for this early stage of research. We next describe the study methodology that we used; then we report our major findings, and finally we discuss their implications for teacher education.

3.2 The Study Methodology

3.2.1 The Teacher Participants

A highly varied group of science and math teachers ($N=72$) participated in our study on a voluntary basis. They taught different subject matters in the sciences (physics, biology, chemistry, natural sciences) and mathematics, at different grade levels (46 junior high teachers and 26 high school teachers) in different schools in northern Israel; had a wide range of practical experience (19 teachers with more than 1 year of experience, 13 with more than 6 years, and 40 with more than 10 years); were mostly female (54 vs. 18 males); and represented different Israeli sectors (41 Jews and 31 Arab, Bedouin, and Druze). Volunteers were recruited from schools, teacher centers, and master's degree programs in one college and one university; hence, the sample was quite representative of the general population of teachers in northern Israel. Most teachers were from average socioeconomic backgrounds, all had at least a B.A., and many had an M.A. degree or were studying toward it.

3.2.2 Task Descriptions

We designed three tasks: (a) spontaneously self-generating VRs of different types to represent diverse textual scenarios; (b) choosing a single VR to best represent each textual scenario, out of a set of four VRs presented; and (c) reasoning about both their self-generated products and their choices of ready VRs – in writing and in interviews. The textual scenarios and the sets of provided representations were carefully designed to include elements and aspects that would reveal teachers' knowledge of the visualization domain. The tasks were validated by five experts in visualization, science and math, and in assessment. These experts were asked to perform the task and comment on verbal or conceptual problems within the task, lack of clarity, inconsistencies, or ambiguous use of language. Tasks and their phrasing have been revised accordingly. To complement these data, we also conducted in-depth semi-structured interviews with teachers based on their products and their reasoning. Altogether, these self-generated VRs, selected VRs from given multiple choices, and teachers' reasoning constituted means for revealing teachers' considerations, rationales, and thoughts while representing information or while relating to given representations within the context of specific, diverse tasks. Thus, this analysis enabled the identification of some aspects of teachers' representational competence, including their specific strengths and difficulties.

Let us emphasize that we never told teachers that their products should be efficient and suitable for teaching. This is important because we sought knowledge that constitutes the basis for developing pedagogy but is not necessarily the pedagogy itself. However, we cannot exclude the possibility that implicitly teachers had instruction in mind.

3.2.2.1 VR Self-Generation Task

To assess the quality of teachers' self-generated VRs for diverse learning materials, participants were asked to: (a) read three different textual scenarios, presented in Appendix A; (b) generate one VR for each scenario that best suited the defined task ("Generate a VR to describe…"); and (c) explain each representation and reason about its efficacy in responding to the task ("Explain the representation you have created. Why do you think it responds to the task requirements?"). These three-types of scenario have been chosen to involve three different types of information representation and processing. One that relates to a process (representing events over time), another that involve quantitative information and in the third required a comparison between inferred and explicit information. All three scenarios were designed as somewhat different than the common, familiar representations used in schools by including a challenge to prevent a ceiling effect.

Time was unlimited, but, for each self-generated VR, teachers were asked to indicate the exact starting and finishing times at the top and bottom of the task form, respectively. Although time duration may reflect teachers' investment of effort in the task (more efforts correlating with longer duration), it also may indicate the task's general level of difficulty or teachers' variability in proficiency.

Scenario 1: Classroom discipline. The text described a process, comprising a simple series of events concerning discipline and classroom management, including the challenge of representing a separate event that may produce a new linear chain of events (See Appendix A). After reading this scenario depicting the process of handling the conduct problems of a boy named Amir over time, teachers were assigned the following task: "Generate a VR to describe the process of handling Amir in terms of his behavioral infractions."

Scenario 2: Yellowettes growth. This text described a set of quantitative data regarding certain ecological conditions (i.e., average elevation above/below sea level and average annual precipitation in mm) and a related independent variable (average number of Yellowettes per km^2 – a fictitious name to exclude any use of prior knowledge of ecology) in different geographical locations. The challenges in this scenario evolved from having to represent three (rather than two) different variables and from having to disregard some presented redundant information (See Appendix A). After reading the Yellowettes scenario, teachers were assigned the following task: "Generate a VR to describe the salient trends in the growth of Yellowettes in their natural environment."

Scenario 3: Poem on Margaret Ann. This text comprised a poem describing a special girl, who may be inferred as different from the other, neighboring children (see Appendix A). After reading the poem, teachers were assigned the following task: "Generate a VR to describe the relations between Margaret Ann and the other children." The challenge in this case is the complexity inherent to poetry (). Poetry involves more complex interpretations and inferences than the other informative texts and is outside the realm of science and math teachers' formal education. However, this third scenario was included in the self-generation task for two main reasons: (1) We believe that representational knowledge enables individuals to represent any given scenario, even if the representation involves an interpretation of that text. (2) A task requiring interpretation may reveal teachers' constructed meanings of what a representation is when encountering less familiar representations in a discipline other than their own. These data will also enable future comparisons of representational competence between science and math teachers and teachers in other domains.

In line with the contents studied and taught by science and math teachers, familiarity with these three scenarios (i.e., prior experience with suitable representations) was probably highest for the Yellowettes text, moderate for the text on behavioral infractions (although processes are quite common in the sciences), and lowest for the Margaret Ann text. The possible effect of teachers' prior science and math knowledge and of conceptual difficulty (i.e., the poem) was neutralized by using simple contents in the task. This simple content enabled participants to direct efforts toward representing and processing rather than toward retrieving prior complex domain knowledge and transferring it to the present case.

3.2.2.2 Multiple-Choice Task

After teachers completed the self-generation task, the teachers revisited each of the three aforementioned scenarios, but this time they received a set of four ready VRs for each (see Appendices B (1, 2, 3) respectively). Teachers were asked to select which of these four VRs best represented the scenario. The four representations differed in type, accuracy, and sophistication; thus, their effectiveness in representing the scenario's information could be ranked from most to least effective. However, choices were not self-evident and could be carried out only after a thorough examination of each representation's details.

Again, time was unlimited, but teachers were asked to indicate the exact starting and finishing times for task completion in designated locations on the task form. The task included: (a) phrasing a label (heading) for each of the four representations; (b) selecting the representation best suited to the task; (c) justifying this choice; and (d) explaining why the other three representations were found inappropriate. Because producing a representation demands considerably more complex operations than choosing one, the multiple-choice task revealed if teachers, given the opportunity, would choose a ready representation that differed or that resembled their own self-generated VR. Moreover, because each representation had its limitations, the teachers' choices and their reasoning objectively revealed the extent of their awareness about the kinds of advantages and disadvantages characterizing each of these representations.

3.2.2.3 Interviews

One-on-one in-depth semi-structured interviews are useful tools in helping participants explain their understanding of certain phenomena (Coll and Treagust 2003). The information collected via teachers' interviews complemented their self-generated products, ready VR choices, and written reasoning responses. Teachers' written responses are often brief and lack detail, probably due to difficulties in articulating knowledge (Loughran et al. 2004). In the interviews, teachers were asked to explain their self-generated VRs, to explain their criteria for judging ready VRs, to characterize and point out the different features of diverse VRs, and to describe their own difficulties, doubts, etc. Interviewees (about 10 % of the participating teachers) were selected according to diversity of performance in order to more fully understand the range of perceptions and constructed knowledge regarding VRs.

3.2.3 Product Analysis

Content analysis was performed on the generated and the selected representations and on teachers' written and transcribed oral answers. Directed content analysis (Hsieh and Shannon 2005) was selected for its reliance on the researchers' expertise in the domain. The uniqueness here is that some of the content was presented as VRs rather than text, requiring our development of specific analytic categories for each of the generated representations to reveal teachers' knowledge. This set of categories was partially theory-based and resulted from a fine-grain analysis of the representation-types used in this study, and partially evolved from teachers' products, following an initial scanning of them, in order to reflect participants' ideas. For example, for the classroom discipline scenario we examined if the VR represents a process, if it is consistent or if it involves interpretations. For the Yellowettes growth scenario we examined the VRs'-type, the representing of a trend, or if the axes units are indicated properly. For the poem we examined for example, if the VR was generalized or specific, or the number of characteristics represented in it. Some general categories could be applied to all representations like, the extent to which participants chose or created a VR *relevant* to the assignment (e.g., Yellowettes' trend of growth in their habitat); (a) the *type* of VR generated or chosen (e.g., a table, graph, drawing, etc.); (b) the *conventions* applied in the generated VRs (e.g., using the Y axis to describe the dependent variable in a graph); or (c) the extent to which the scenario's *data* were depicted in the VR. The final set of categories, therefore, blended domain knowledge and teachers' products. Although we have scored teachers' performance according to the final set of criteria, we would attend to them in this chapter only as related to time. Some frequencies were calculated for different categories.

3.2.4 Procedure

Prior to the first task, teachers received a short explanation regarding the goal of the study and the concept of "VR" as an effective visual mode for representing information, and teachers completed a short demographic questionnaire. Initially, they received only the self-generation task, and were asked to return it in person at the location of their recruitment the next week. Only after its submission did they receive the multiple-choice task, to prevent them from making any changes to their self-generated VRs in light of the ready VRs they encountered. They submitted the second task 1 week later. All three researchers analyzed the teachers' data, first to identify additional categories and then to code the data according to the final category set. Seven of the teachers (~10 %) were asked to be interviewed based on their submitted tasks.

3.3 Findings: How Did Teachers Perform and What Did They Know About Visualization?

A rich set of data emerged from this qualitative analysis of teachers' products and interviews. Overall the teachers showed poor visual competence. Table 3.1 presents an overview of the types of VRs that teachers preferred to generate on their own and to select from ready options, to best represent each of the three scenarios depicted in texts. In the current chapter, we decided to focus on several general findings that hold direct implications for teacher education and science and math teaching: the importance of language, difficulties in phrasing headings, preference for simple and familiar representations, performance time, the influence of prior knowledge, and preferences' stability.

3.3.1 The Importance of Language

Language is both a communicational device and a cultural characteristic. Two distinct language-related phenomena were revealed in teachers' products as described next.

Table 3.1 Distribution of visual representations (VRs) generated and selected by teachers for each scenario, in percentages (N = 72)

		Self-generated VR type							Selected VR type from four ready choices			
	Optimal VR type	Iconic	Line graph	Bar graph	Table	Chart	Map	Other	VR 1	VR 2	VR 3	VR 4
Scenario 1: Discipline ("process")	Flow chart, A series of pictures of different states	4	6	3	6	80	0	1	Flowchart 25	Table 30	Chart 39	Graph 6
Scenario 2: Yellowettes ("trend")	Line graph	1	17	31	33	13	3	2	Pie graph 15	Line graph 52	Table 28	Map 5
Scenario 3: Margaret Ann ("relation")	Table, iconic	51	0	1	7	35	0	6	Illustration 39	Table 38	Chart 13	Concept map 10

3.3.1.1 Task Semantics as Related to Teachers' Preferred VR Types

For Scenario 1, 80 % of the teachers chose to generate a chart to depict the process of handling Amir's behavioral problems over time (see Appendix A). The word "process" used in the assigned self-generation task (*mahalach* in Hebrew, which means "in the course of") seemed to stimulate teachers' usage of words referring to a process or series of events. In addition to "process," their reasoning (written and in interviews) included the words "evolution," "chain of events," "development of events," "proceedings," or "gradual transition among stages." Because all four of the VR options presented in the multiple-choice task (see Appendix B1) represented processes, teachers' choices could not be regarded as additional evidence for a connection between task semantics and choice of VR type.

The word "trend" (*megama* in Hebrew) appearing in the assigned self-generation task for the Yellowettes scenario (see Appendix A) influenced some teachers' preferred self-generated VR types. For example, a minority of teachers explained their preference of a self-generated graph as "based on the description of the quantitative data presented in the scenario, which required a graph." Only about 17 % of the participating teachers created a line graph in the self-generation task, whereas the majority (83 %) attempted to illustrate a trend by generating inadequate VRs. About 33 % of the teachers preferred to generate a table for this scenario, but only about half of them (15 % of the teachers) displayed a table in which the requested "trend" was represented by arranging one of the variables in descending order. While reasoning, teachers used words like "dependency," "relations between variables," and of course "trend." It seems that in this case the scenario stimulus activated various schema and only in few of them a description of numerical data is represented by graphs. In contrast, in the multiple-choice task, the word "trend" did appear to impact teachers' preference for a ready line graph among 52 % of teachers, (see VR 2 in Appendix B2) evidencing these teachers' correct perception of line graphs as representing a "trend" for quantitative data. Understandably, selecting from a set of given choices is easier than generating one's own representation from scratch. Interviews confirmed that many teachers had difficulties in generating a line graph to represent the relations between three variables (elevation, precipitation, and plant growth per km^2), which required the application of multiple cognitive operations.

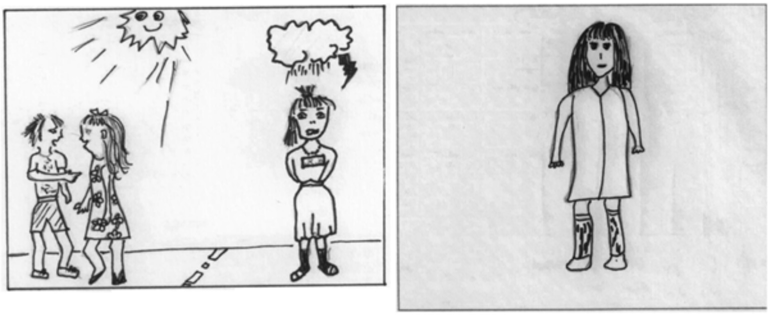
The word "relation" (*mah bein* in Hebrew, meaning "what is between") appearing in the assigned self-generation task for the poem about Margaret Ann (see Appendix A) seemed to influence teachers' preferred self-generated VR types. Indeed, 64 % of the teachers generated a VR that explicitly represented a comparison or contrast between Margaret Ann and other children. While reasoning about their creations, teachers used wording such as "opposite to," "difference," and "relations," and they described in great detail situations of "her versus others." Like for Scenario 1 (discipline), because all four of the VR options presented about Scenario 3 (the poem) for the multiple-choice task (see Appendix B3) represented comparison/contrast, teachers' choices could not be regarded as additional evidence for a connection between task semantics and choice of VR type.

3.3.1.2 Effect of Semantics

These findings pertaining to the important role played by task semantics provide support to prior research outcomes in different areas, like the effect of the wording used in math word problems involving adding, subtracting, etc., on students' performed operations (e.g., Nesher et al. 1982; Valentin and Sam 2004), or the effect of how choices are described or framed in the task on people's decisions regarding risk preferences (Wang 1996), and more. Awareness of people's responses to semantics, words, and grammar should increase researchers' sensitivity to how study tasks are phrased. Nevertheless, when the objective of a task is to examine *what kind* of VRs individuals may generate for a given text scenario, as defined in the present case, even greater caution should be applied. As shown above, the words used to describe the general characteristics of the referent – be it a process, trend, or relation – determined to a great extent the type of VRs generated or selected. It seems that an intrinsic link exists in the minds of teachers between specific words and certain VR types. This mental link may lead teachers to generate or select a VR without deeply understanding the particular characteristics that make each VR efficient for representing a specific scenario. For example, perceiving trends in Tables that contain a large set of data is difficult, and this VR should not be selected over a graph to show a trend. Tables are better for making comparisons. Such a link may fail to activate the correct type of representational knowledge due to each VR type's many variations, which require comprehension of what they mean and what they can represent. These revealed links between linguistic terms and VRs should be deeply examined and refined so that teachers can generate precise VRs to fit specific tasks related to described textual scenarios.

3.3.1.3 Sensitivity to Linguistic Complexities as Related to Teachers' Representational Efficacy

VRs' advantages are affected by cultural factors (Eilam 2012), among them the language. The composition of our study population enabled us a limited examination of this assertion. For science and math teachers, the understanding of a poem, even if brief and written in simple Hebrew, was expected to require a higher sensitivity to language than in cases of descriptive texts. In addition, representing a poem involves some interpretation, rather than only a strict mapping between referents and representations. Hence, it was not surprising that in the current analysis Jewish science and math teachers performed significantly better on Scenario 3 than their Arab counterparts for whom Hebrew is a second language, whereas the two groups did not differ in their performance on the other two scenarios. Israeli Arabs seeking higher education regularly attend Hebrew-speaking universities and inservice programs and usually master Hebrew sufficiently to understand the content studied, to express their ideas, and to perform the required learning tasks (e.g., writing seminar papers, giving presentations). However, their deficient sensitivity to linguistic nuances, to the many layers of language and its complexity, emerged



The Jewish teacher's VR The Arab teacher's VR

Fig. 3.1 Representative Jewish and Arab teachers' visual representations (VRs) of Scenario 3 – the poem about Margaret Ann

when attempting to visually represent the Hebrew-language poem. Arab teachers' self-generated products communicated the poem message less efficiently, missing nuances in the communicated meaning. Figure 3.1 presents self-generated representations of the Margaret Ann task by representative Arab and Jewish teachers. Both attempted to represent details about the referent, but the Arab VR represented Margaret Ann alone, while disregarding the implied information about others who were hinted to in the Hebrew poem. The Jewish VR included those others.

Our claim regarding the effect of language was strengthened by the finding that Arab-Jewish differences in scores were lowest for the quantitative scenario ("Yellowettes"). To represent the poem, deep understanding of the text was required, whereas to represent the plant growth scenario – which is more familiar to science and math teachers – fewer efforts were needed. Interestingly, none of the Arab teachers (both in interviews and in their written explanations and reasoning) felt that the Hebrew language hindered their performance. They all felt that their Hebrew was more than adequate to perform the visualization task and rejected the need for translating the scenarios and tasks into Arabic. Such deficient awareness of possible language constraints on the part of the Arab participants themselves and on our part during the study design is alarming, due to the many implications of this phenomenon for current educational systems, as discussed at the end of this chapter.

3.3.2 Difficulties in Phrasing Representational Headings

Headings of VRs extract the information represented in them and are necessary for understanding them. Hence, headings may constitute another source of data regarding teachers' knowledge of representations. Many teachers (83 % for Scenarios 1 and 3; 76 % for Scenario 2) exhibited a deficient ability to phrase a heading for the provided VR. Among those who experienced difficulties in this task, there were many who simply indicated the word describing the VR type (e.g., graph, table, flowchart, drawing), or ignored this part of the task altogether. Phrasing a heading involves two operations: first to identify the characteristics of the VR at hand (e.g., a graph represents relations between variables), and second to phrase the appropriate wording. Both operations require the investment of additional efforts. Therefore, teachers' low performance may have stemmed either from deficient knowledge of VRs' functions or from reluctance to invest additional efforts. Another possibility is that teachers interpreted the word "heading" as a call to merely identify the VR type rather than to detail the representation's function.

3.3.3 Preference for Simple and Familiar Representations

A salient phenomenon was teachers' preference of simple, prototypical VRs, which required minimum mental effort to generate and interpret, and which sometimes precluded teachers' selection of more effective representations. Preference may be guided by efficacy. It is possible (as found for the graph in the Yellowettes scenario) that when teachers faced great difficulty in representing or understanding VRs, they "escaped" to the simpler ones perceived almost as effective. In teachers' written reasoning and in their interviews, teachers explained this attraction to simple VRs, both when generating a VR and when choosing a ready VR: "This representation exhibits the stages in a simple and clear way, which is comfortable and easy on the eye;" "Because it is easy to get, organized and convincing;" "It is easy to quickly find the details;" "This representation is simple, easy to understand and easy to use." The search for an easily perceived and interpreted VR is of course a great advantage for clear transmission of information; indeed, clarity is an important rationale for utilizing VRs in addition to texts. However, such a consideration should not override representational accuracy, and unfortunately, sometimes teachers chose simple VRs instead of accurate ones in cases where the optimal choices required more complex representations.

3.3.3.1 Preference for Tables

Many teachers generated or selected a table VR when feasible. In the self-generation task, this tendency was especially prominent for the Yellowettes scenario, where about 33 % of the teachers generated a simple table even though a line graph would have been a more efficacious choice to represent the complex growth trends. In the second part of the task many have selected the table (30 %) and chart (39 %) for representing the process in the discipline scenario. In their written reasoning or interviews teachers explicitly indicated that they chose to generate a table for Scenario 2 because of their difficulty in creating a graph to represent all three variables (i.e., precipitation, elevation, and number of Yellowettes). Also, in the multiple-choice task, along the three scenarios between 28 and 38 % of the teachers selected the ready table from the four VR options presented as shown in Table 3.1, even though the presented tables were not the most suitable representations at least for the discipline and the Yellowettes scenarios (as seen in Appendix B1 and B2).

3.3.3.2 Tables Familiarity

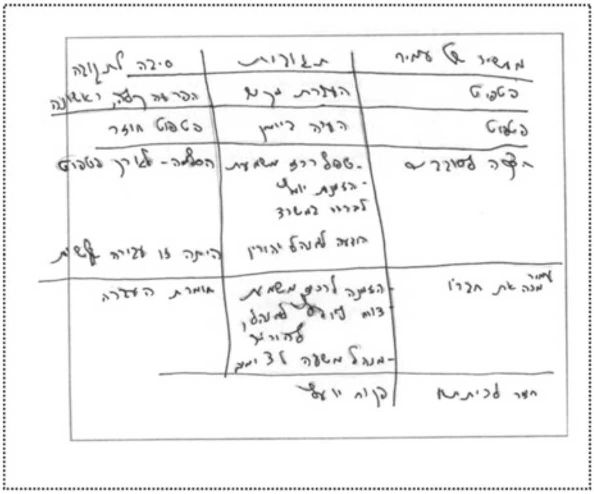
Tables are highly familiar to teachers, due to their extensive use in school in all subject matters, and due to teachers' constant exposure to tables in diverse contexts including their own days as school students, their teaching career, and their general everyday use of tables from the media, brochures, and so forth. Tables boast some important affordances, including: organization of many given details, comparison among different values of variables/categories, perception of relations among items located in the same table row, and even revelation of a trend if a single independent variable is arranged in ascending or descending order for a small amount of data. Such widespread context-based usage of tables usually results in high cognitive flexibility regarding their application (Spiro et al. 1988), which can enable teachers to effortlessly use tables to represent diverse contents or referents. However, the desire to oversimplify VRs does not always address specific task demands.

3.3.3.3 Teacher-Generated Tables

As a rule, the teachers' self-generated tables did not utilize their affordances. Mostly, teachers used tables as a framework for sorting the referents' data, for organizing data to a certain extent, for comparing data without using categories, or, more rarely, for revealing a trend, which was difficult to elicit if teachers did not arrange the independent variable's values (e.g., the height in relation to see level or the rainfall) in ascending/descending order. Many times, self-generated tables did not respond to task requirements.

Figure 3.2 presents one teacher's representative three-column table aiming to visually represent the first textual scenario on the process of handling Amir's behavioral infractions. As seen in the translated table, in the left-hand column each of Amir's different behaviors are organized on a new row in ascending order. The central column presents the different responses to each of Amir's behaviors, indicating who enacted them, on the same rows as the behaviors listed in the first column. The right-hand column is redundant, repeating some of Amir's behaviors with few explanatory remarks. In her written reasoning for this choice of self-generated table, the teacher wrote that it represents "the story of an act – a response – a reason for the response, and the rows progress in chronological order."

Figure 3.3 presents one teacher's representative four-column table aiming to visually represent the second textual scenario on the growth trends for Yellowettes. As seen in the translated table, each row represented the variables' data for a specific location ("area") and each column represented a different variable: average annual precipitation in mm, elevation in meters above/below sea level, and average number



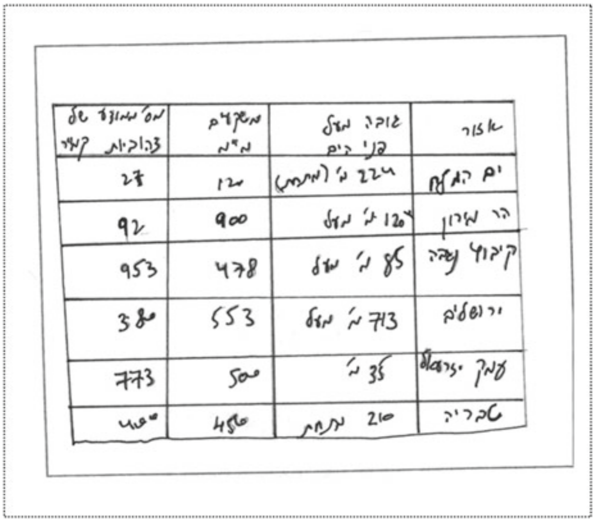
Here please draw a visual representation that suits the task, in your opinion.

Amir's behavior	Reactions	Reasons for reactions
Chatting	Moving to a new seat	Light disturbance, first
Chatting	Teacher comments in the classroom log	Repeated chatting
Harassing nearby students	– Disciplinary officer's handling – Event clarification in the counselor's office – Note to principal and parents	Escalation – not chatting only This was the 3rd behavioral infraction
Hitting his friend	– Disciplinary officer's handling – Report to the counselor, teacher and parents – Suspension by principal for 3 days	Severity of the infraction
Returning to his classroom	Counselor supervision	

Fig. 3.2 Sample table self-generated by one teacher to visually represent the given text in Scenario 1 Discipline: Original Hebrew and translation to English

of Yellowettes per km^2. However, none of the three variables was arranged in an order that would reveal the trend as required in the task. The teacher's written reasoning stated: "This representation explains everything that was mentioned, and anybody, even if they did not read the represented [scenario], can immediately understand the data."

Figure 3.4 below presents one teacher's representative table aiming to visually represent the third textual scenario on the relations between Margaret Ann and neighboring children. Utilization of a table to make comparisons between items (in our case – Margaret Ann and others) illustrates a widespread practice among many

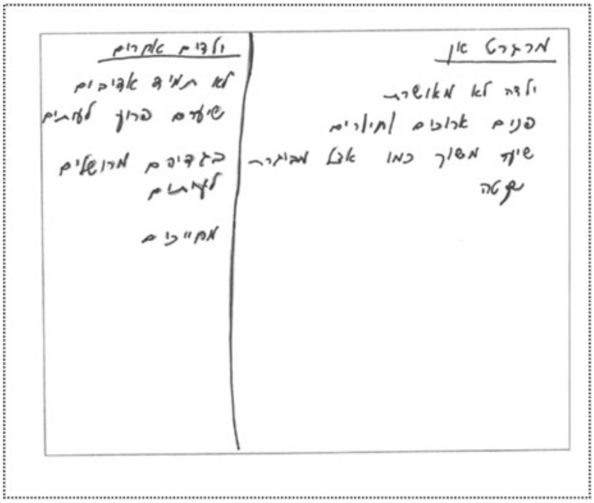


מס' ממוצע של צהוביות קמ"ר	משקעים מ"מ	גובה מעל פני הים	אזור
27	120	224 מ' (מתחת)	ים המלח
92	900	1204 מ' מעל	הר מירון
953	478	85 מ' מעל	קיבוץ נגבה
380	553	713 מ' מעל	ירושלים
773	500	35 מ'	עמק יזרעאל
400	450	210 מתחת	טבריה

Area	Elevation above sea level	Precipitation in mm	Average no. of Yellowettes km^2
Dead Sea	224m (under)	120	27
Mt. Meron	1204m above	900	92
Kibbutz Negba	85m above	478	953
Jerusalem	713m above	553	380
Jezreel Valley	35m	500	773
Tiberius	210 under	450	400

Fig. 3.3 Sample table self-generated by one teacher to visually represent the given text in Scenario 2 (Yellowettes): Original Hebrew and translation to English

individuals, including teachers. However, as seen from the translated two-column table in Fig. 3.4, which was typical of several teachers' products for this task, the table was generated in a way that hindered effective comparisons. A vertical line divided the page into two columns, and each item was described distinctly in its own column with no relation to the description of the other item in the other column. Such a VR does not apply any values for comparison (categories) and does not place similar properties on the same row. This teachers' written reasoning about the task revealed: "I performed a comparison between what is told about Margaret Ann and what may be implied about the behavior of other children. In such a comparison, her behavior is salient and shows it was different from that of the others her age, which is what the poem says." This reasoning use the word "comparison" but the outcome table does not reveal an understanding of how such a comparison should be represented.



Here please draw a visual representation that suits the task, in your opinion.

MargaretAnn	Other children
Not a happy girl	Not always polite
Long pale face	Their hair is often wild (uncombed)
Hair drawn back like adult	Their clothes are often sloppy
Quiet	Smiling

Fig. 3.4 Sample table self-generated by one teacher to visually represent the given text in Scenario 3 (Margaret Ann): Original Hebrew and translation to English

3.3.3.4 Preference for Other Simple VRs

As seen in Table 3.1, when selecting the optimal VR type from the four ready options in the multiple-choice task, among the 70 % of teachers who did not choose the table (VR 2) to represent Scenario 1, over half (55 %) preferred the simple chart (VR 3 – Appendix B1) whereas only about one-third (36 %) chose the complex flowchart (VR 1 – Appendix B1). Yet, this simple chart's increasing circle size, used to represent the escalating behaviors and punishments, did not coincide exactly with what teachers were asked to represent. Similarly, for Scenario 3 – the poem on Margaret Ann – 39 % of the teachers chose the simple faces (see VR 1 in Appendix B3), which is more than the percentage of teachers who chose the table (VR 2–38 %), regardless of these faces' inadequacy for effectively representing the task objective. The illustration of many happy faces versus Margaret Ann's sad face was simple to perceive because it ignored a great deal of information and allowed some bias in representing the remaining information.

To summarize these findings, teachers demonstrated a tendency to choose simple and effortless VRs and particularly exhibited a preference for tables and flexible usage of tables for different purposes. Alas, their performance even with this simpler VR revealed various difficulties. The main problem evident from many teachers' attempts to visually represent the textually presented scenario data was that their VRs were ineffective in promoting the ability to better perceive the data represented in the text. More specific difficulties like the use of units on the axes of the generated graphs are discussed below. To effectively convey accurate information, the search for a simple representation of data should be guided by knowledge about VRs; however, these teachers had received no formal, intentional, organized learning of this topic. Therefore, the teachers seemed to base their considerations on their wide experiences with VRs and on their intuitions only. This tendency holds some important educational implications.

3.3.4 Performance Time for Creating VRs

Large variance emerged in teachers' self-reported time duration for producing VRs. Self-generation of a VR required 2–40 min for Scenario 1 ($M = 8.53$, $SD = 6.60$), 2–60 min for Scenario 2 ($M = 14.18$, $SD = 11.42$), and 1–26 min for Scenario 3 ($M = 7.35$, $SD = 5.77$). This variance may stem from different teacher characteristics and behaviors such as teachers' attitudes toward the task, representational abilities and difficulties, and investment of effort in all phases of the task (reading the text, attempting to represent the scenario's details fully and accurately). Variance may also have its roots in different task characteristics such as tasks' complexity, tasks' correspondence with teachers' science and math domain knowledge, and specific VRs' pervasiveness. For example, Scenario 2 on "Yellowettes," which was expected to be most familiar and accessible to science and math teachers, required a longer amount of time on average for creating a VR, with the largest standard deviation, probably because of its complexity that necessitated representation of three variables. Notably, those teachers who created a "pseudo-graph" completed the task in a shorter time.

Nevertheless, this duration range provides some notions about teachers' performance. Although no significant correlation emerged between the score achieved for each scenario and the time duration of its performance for either the first or second scenarios, a significant positive correlation did emerge for the Margaret Ann scenario, $r = .34$, $p < .05$. Namely, teachers who invested more time in reading the poem and creating a VR to represent it demonstrated a better performance. Probably this result reflects the need to invest more time in reading the poem in order to understand and interpret it as related to the given task. The large variance in time has also been found for selecting VRs, but the time required for selecting each representation was much shorter than for generating it: for Scenario 1 ($M = 5.82$, $SD = 3.57$), for Scenario 2 ($M = 7.11$, $SD = 5.09$), and for Scenario 3 ($M = 5.53$, $SD = 3.16$). In addition, no significant correlation between performance and time was found. These

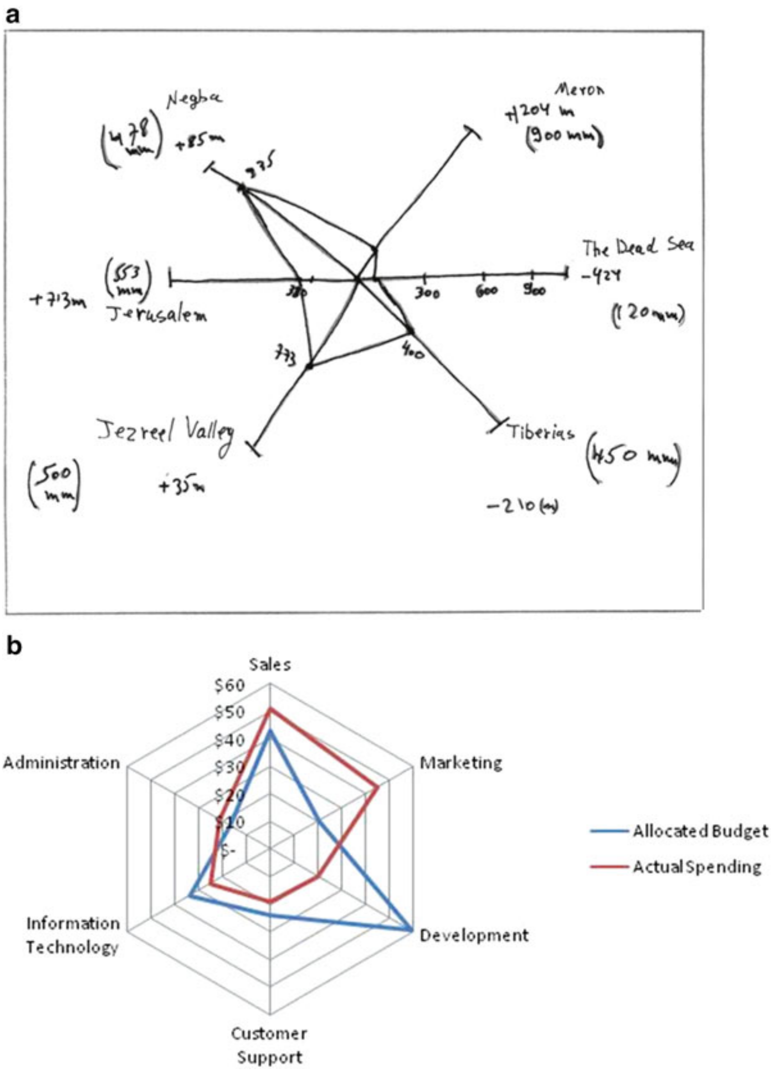


Fig. 3.5 Influence of domain knowledge on a physics teacher's self-generated visual representations. (**a**) Physics teacher's spider chart representing Yellowettes (Scenario 2) (**b**) Spider chart representing budgeted and actual spending for a given organization (David Clement 2013)

results may suggest that as expected, selection is easier than generation of VRs requiring less efforts. However it may also hint at the superficial examination of the properties of each VR, as expressed in the short time invested in it and as is also conveyed by teachers' reasoning about their selections.

Another phenomenon related to time duration was its relationship with teachers' preference for simple VRs. Those teachers who generated a table to represent the "Yellowettes" text scenario invested less time ($M = 11.17$ min, $SD = 8.21$) than those

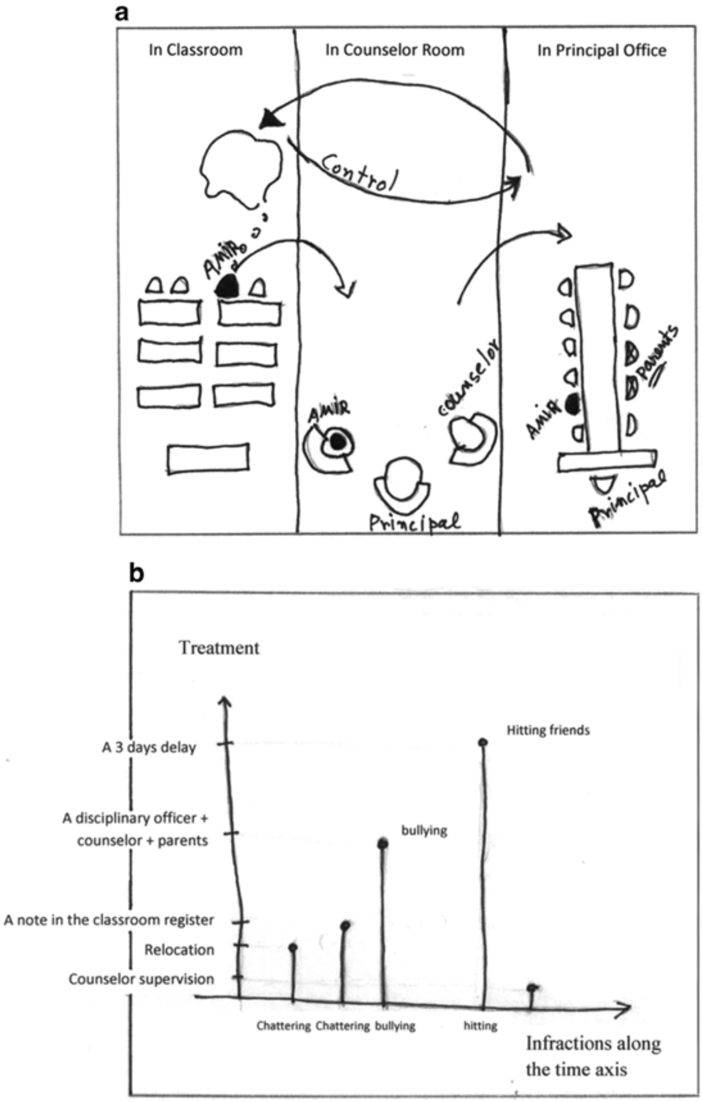


Fig. 3.6 Influence of teachers' domain knowledge on their self-generated visual representations to represent handling of Amir's behavior (Scenario 1). (**a**) Architecture-based visual representation (**b**) Bar graph expressing educational views

who generated other VR types like bar graphs ($M = 18.06$ min, $SD = 12.99$), line graphs ($M = 13.33$ min, $SD = 12.87$), or others ($M = 11.46$ min, $SD = 13.04$). This suggests teachers' great familiarity and flexibility with tables, which required less time and probably fewer efforts.

3.3.5 *The Influence of Prior Knowledge*

The effects of prior knowledge on any aspect of learning and knowing are well established. Teachers' prior knowledge includes knowledge of content, representations, procedures, and pedagogy, as well as teachers' attitudes, beliefs, and life experiences. The influences of some of these existing bodies of knowledge clearly emerged in several findings in teachers' self-generated VRs and in-depth interviews. Although such influences may be expected, we next present some examples (see Figs. 3.5 and 3.6) that offer implications for the use of self-generated VRs in education.

3.3.5.1 Physics Teacher

As seen in Fig. 3.5a, one physics teacher generated a spider chart (also called a radar chart) to visually represent Scenario 2's Yellowettes, explaining: "In this task there are many variables that have to be assembled. I believe that the best representation would be the graphical one. I chose a graphical representation called the spider, in which a large amount of data may be assembled."

This teacher probably decided to generate this chart type because of his prior knowledge or familiarity with it from the physics domain. Indeed, such charts are used in many domains like the sciences and economics for representing small-to-moderate-sized multivariate data sets (e.g., see Fig. 3.5b). Spider charts can expose patterns in data if the observations are arranged in some non-arbitrary order. However, in the case of the Yellowettes, this teacher's choice of the familiar VR type was inappropriate because the self-generated spider chart simply presented plants' locations arbitrarily, without showing any trends as requested in the task.

3.3.5.2 Architectural Background

Figure 3.6a presents the unusual VR generated to represent the school's handling of Amir's disciplinary infractions by a teacher who indicated in her interview a strong personal interest and bachelor's degree in architecture. As she explained, her VR was a sketch of the various school rooms in which Amir's infractions were handled. She explained that the details exhibited in each room characterized the specific rooms, such as pairs of desks in the classroom, face-to-face seats in the counselor's room, and the long table for meetings in the principal's office. She explained that her use of arrows depicted the "process" of handling the boy's disciplinary infractions: "I drew Amir moving from one functionary to another for handling. I separated the different authorities, and described his move from one place to another because I view the school as having cyclic processes (from the classroom to the different authorities and back to the classroom under control). The entire control process occurs in cycles."

3.3.5.3 Artistic Background

Another teacher with domain knowledge in the arts (he studied art and drawing during his bachelor's degree) likewise generated a picture-like VR to represent Scenario 2 on the Yellowettes. His written and verbal interview explanations indicated that he prefers to "draw everything for students," which may clarify his preference for this VR type despite its ineffectiveness in transmitting the plant growth trends.

3.3.5.4 Educational Views

Many teachers expressed general educational views and perspectives through their products. For example, Fig. 3.6b presents one teacher's self-generated bar graph for Scenario 1, where she plotted Amir's "infractions over time" as the x axis and the "handling" on the y axis. Despite lacking data regarding units for measuring behavioral problems or levels of punishment, this teacher imposed her own perspective by placing the various aspects of "handling" in different positions along the y axis. From her deletions, it is evident that she debated about where to insert each item, and she even qualified her placements in her written explanation by stating: "Of course we have no data concerning what the child experienced and why he behaved the way he did." Thus, this teacher's perceptions about school discipline superseded her need to represent the event according to the task requirements.

Additional statements by other teachers supported this phenomenon: "The representation shows the severity of the handling in each case, but the school's reaction was too harsh and unnecessary" or "My sketch shows that the school counselor has the most important role in taking care of this event, because the worst it [the behavior] becomes, the more the counselor is involved."

3.3.5.5 The Affect Fallacy

Last, the effect of teachers' affect also emerged in many of their comments, both in writing and in interviews, like: "I can't relate to this representation" or "I did not feel comfortable with it." Such remarks suggest that subjective rather than objective and professional considerations were applied for generating and selecting VRs, probably due to teachers' deficient formal education in the topic.

3.3.6 Preferences' Consistency

Our findings showed that more than half of the teachers (67 % for Scenario 1, 60 % for Scenario 2, 67 % for Scenario 3) used one VR for the self-generated task but then chose a different VR as the optimal representation for the text when given the four ready VRs in the multiple-choice task. These changes sometimes improved the effectiveness of the teachers' first choice (the self-generated VR), but at other times decreased effectiveness. Some teachers were compelled to change their preferred VR type in the multiple-choice task because none of the four ready VR options matched their own self-generated VR type. Yet, this near-randomness of the results suggests that teachers may feel insecure about their abilities in the area of representing textual data visually, calling for teachers to receive constructive tools for promoting visual literacy skills.

3.4 So, What Have We Learned from Teachers' Products and What Are the Implications?

Teachers must deal with so much in their classrooms: They need to master domain content, become expert at learning and teaching strategies and skills, manage their classrooms, create effective learning environments while tending to the complexity of factors interacting within them (e.g., social, personal, cultural), and engage their students in a productive process of learning for which they select suitable learning materials or produce different learning aids. Teachers formally acquire relevant knowledge in the course of their science and math discipline study, teacher education programs, and advanced higher education degrees, and frequently also in inservice programs along their careers. It is no secret that teachers must continuously master increasing amounts of knowledge in all these areas – both new up-to-date domain-related contents (especially noted in the rapidly developing sciences) and educational contents (concerning human learning, psychology, sociology, etc.), as well as new and innovative modes of instruction, pedagogies, or curriculum. Knowledge of representations and particularly VRs is one of these rapidly developing areas that teachers need to master, because VRs are relevant to all contemporary educational practices.

However, teacher education programs already struggle to incorporate all these areas of proficiency while maintaining deep professional study. The possible introduction of representational skills and VR literacy to these programs competes with the introduction of other important areas, and has been sufficiently investigated empirically to date. Therefore, the entrance of visual literacy has been delayed in most programs. Only a few existing programs today have implemented relevant courses or have integrated specific visualization issues. Considering this state of the art, why should teachers be expected to know more about visualization than the average citizen? Why should they be able to deal with all the new, highly varied modes of static and dynamic VRs that are penetrating all learning environments through textbooks, internet, software, and so forth? Why should teachers demonstrate an ability to develop new pedagogies for utilizing VRs, for generating them, or for adapting existing VRs to fit their students' characteristics? Some of these questions may be answered only by policy makers and programs developers. However, due to the importance of this issue in the visual world, the easy access to VRs, and teachers wide use of VRs, we hope that evidence regarding current teachers' knowledge would be re-considered as being an important and required element of teacher professional development.

Till now, this issue has gained very little attention despite teachers' important role in mediating between students' learning and representations, as well as the recognition that teachers need to continue develop their bodies of knowledge in all areas relevant to teaching. The present chapter has aimed to help stimulate empirical research, professional training, and educational practice by examining some general aspects of teachers' knowledge about generating and selecting representations, as extracted from science and math teachers' self-generated products, preferred choices of ready VRs, and written and interview data on their reasoning processes. The following presents some of the main implications arising from the findings discussed in this chapter.

3.4.1 Language Effects

One of the most important abilities needed to effectively represent information visually is to select the goal for which a VR will be used or created and to identify the specific data, within all the given data, that will best serve to communicate the message for achieving this goal. Frequently, such information is represented by texts and language. Our findings suggest that the task design – our wording of the goal in the presented task in each scenario – frequently influenced teachers' generated or selected VRs. This suggests the need for extensive, systematic research into the different effects of task's semantics and texts' wording on visual choices. In addition, the influence of language was expressed in differences between Israeli Arab and Jewish teachers' performance, suggesting that Arab teachers needed to invest more effort to understand Hebrew texts, despite their generally sufficient mastery of Hebrew that enabled them to successfully obtain higher education.

The implications of language effects are particularly important in today's globally changing world, in which many demographic changes occur due to immigration, resulting in diverse multicultural and multilingual classrooms. This diversity poses a great challenge for teachers. Researchers suggested that there should be a correlation between the learners' mother tongue and the language of instruction (Piper 1993). Most research investigated children learning in a second language environment rather than teachers' using second language for teaching. Such practices are common in many schools over the world today due to immigration. In Israel, for example, many Russian immigrants teach in Hebrew, and some Arabs teach in Hebrew Israeli schools. However, the present case is unique in the sense that the participating science teachers were required to represent a poetic text rather than a science informative text, outside of their field of expertise. Although the revealed differences here were salient mainly in visually representing the poem, differences also emerged in representing the other two textual scenarios, including the quantitative scientific text, suggesting that science and math teachers should be fully aware of these lingual difficulties and develop pedagogies to promote *all* students' success. This is not an easy task, but VRs may offer an international language for teaching science and math and thus may successfully serve this objective. It is worth investigating if a better understanding of "representing and representations" would indeed decrease such lingual difficulties, as found for other cognitive skills.

3.4.2 Simplicity and Communicability of VRs

One of the main advantages of VRs is that they organize the represented information in a way that easily and holistically communicates the message. In this regard, teachers' preferences of simple VRs are justified. Still, when this desire for simplicity disregards relevant details and insight into the essential information, it hinders representational efficiency. Deep understanding of different VRs and their intended messages is necessary to constrain such preferences for simplicity. That is, teachers must learn to preserve the effectiveness and quality of the VR in order for it to achieve its goal. Teachers' preference for simple VRs may offer indirect evidence of teachers' unconscious desire for a lower cognitive load when generating representations and for easier information processing when selecting representations. However, no measure of cognitive load was taken to support this assumption, calling for future research to investigate the effects of data complexity, and to try to pinpoint the stage at which multiple operations or variables become overwhelming for teachers.

3.4.3 Performance Time

A large variety in performance duration was evidenced, probably reflecting teachers' past experiences, knowledge, and motivation to perform. Interestingly, although the investigated population was science and math teachers, they required the longest amount of time to visually represent the multiple variables in the Yellowettes scenario. The difficulties that children encounter with graphs are well documented in the literature (Gattis and Holyoak 1995; Leinhardt et al. 1990; Shah and Hoeffner 2002). However, teachers' knowledge of graphs has not yet been sufficiently explored. Our findings suggest that this is a vital issue calling for further examination, because of its many implications for teaching and learning science and math.

3.4.4 Existing Knowledge Effects

In some cases, these teachers' VRs revealed the activation and retrieval of irrelevant knowledge related to teachers' personal interests or past experiences rather than retrieval of relevant domain or representational knowledge. Such interference by prior knowledge hindered the effectiveness of the VR, by establishing a prior framework for spatially placing the VR different elements. In the same vein, teachers' general educational knowledge regarding different events or stakeholders in the school setting, constructed over many years of professional development and practice, was noticeable in their representational choices. This general knowledge was particularly salient in the VRs that teachers created to represent Amir's behavioral infractions, which went beyond the given data and incorporated teachers' personal value judgments or practices. Instead, teachers' considerations should have applied representational knowledge without integrating subjective perspectives and general pedagogical beliefs about school. Such subjective considerations affected the creation and selection of VRs and overrode representational knowledge-based professional considerations. The implications of submitting to personal tendencies and beliefs while teaching science and math are alarming, suggesting the crucial need for explicit training of teachers on how to extrapolate data objectively.

3.4.5 Unstable Representational Preferences

The findings showed that over half of the teachers shifted to a new VR type in the second task, abandoning their earlier preference for self-generating a VR when given a choice of four ready VR options. Furthermore, teachers' highly diverse products suggest that their body of knowledge regarding representation and VR-interpretation skills remain far from comprehensive and coherent. This instability and diversity in VR choices may have important consequences for teaching and learning science and math and for teacher education programs. It may promote the application of irrelevant, non-based or incorrect considerations for generating/selecting a certain VR for use in specified conditions. Such inconsistency also sends wrong messages to students regarding the characteristics and functions of VRS.

3.4.6 Implications for Science and Math Teachers' Professional Education

The various difficulties identified in teacher performance hold significant implications for professional development programs of science and math teachers. First, the topic of visual literacy and skills for creating and selecting VRs should be explicitly introduced into science and math teacher education programs (Eilam 2012).

Although preservice teachers entering such programs do possess some knowledge of the topic, their knowledge is mostly constructed through everyday experiences with VRs via the media and through exposure during their higher education to specific VR types that characterize their particular science or math domain (e.g., periodic table of chemical elements, computer science flowcharts, histogram for density estimation in statistics).

As seen here, such spontaneously gained knowledge is not enough. Teachers must be the target of systematic, intentional instruction of this topic, which should be delivered in teacher education programs or inservice programs along their lifelong professional development (for K-12 instruction). They need to acquire explicit tools for considering the many issues related to visualization, such as learning which kind of VR to generate for different types of provided information, what kind of data should be integrated in different VRs, how a VR can achieve a set goal, and so on. Such learning will promote teachers' knowledge and representational competence, will raise their awareness of cultural differences (e.g., in language or conventions), will help them recognize the limitations of existing representations (e.g., in software, internet, textbooks), and will advance teachers' science or math disciplinary knowledge as well as their pedagogical professional development. Teachers' improvements in the mindful implementation of VRs in science and math education would certainly affect their students' understanding of the domain studied as well as students' knowledge and understanding of visualization and VRs. Therefore, research regarding teachers' representational competencies is important for the development of different modes for enhancing visual literacy of teachers and students alike. Centering the present chapter on this vital topic is a pioneering endeavor, and we invite researchers to join us in expanding knowledge about this challenge facing present-day educators.

Appendices

Appendix A: Given Textual Scenarios, Tasks, and Optimal Visual Representation (VR) Types

Scenario 1 (Classroom Discipline)

Behavior in the Classroom: Amir chitchatted during the lesson. Because it was a minor behavioral disruption and his first, the teacher decided to move him to a different seat. When Amir chatted again, the teacher decided to write him up in the classroom log. But after he bullied nearby classmates, his case was handed over to the school's disciplinary officer for handling. The officer decided that the school counselor should also attend the inquiry in the office. Because this was Amir's third disciplinary problem, a message was also sent to the principal and the student's parents. A month later Amir was caught hitting his classmates during a lesson and was immediately sent to the disciplinary officer due to the severity of his behavior. The incident was also reported to the school counselor, the principal, and the parents. The principal decided to suspend Amir from school for 3 days, after which he returned to class but remained under the counselor's supervision. **Task:** Generate a VR to describe the process of handling Amir in terms of his behavioral infractions.

Scenario 2 (Plant Growth Rates)

The Distribution of Yellowettes. Israel is very versatile in its topography and plant life. Between April and May of 2012, the distribution of Yellowette plants per square kilometer was measured in Israel. In order to depict Yellowettes' growth, two variables were measured, average elevation above/below sea level and average precipitation in a number of locations: the Dead Sea (424 m. below sea level), Mt. Meron (1,204 m. above sea level), the Negba Kibbutz (85 m. above sea level), Jerusalem (713 m. above sea level), Jezreel Valley (35 m. above sea level), and Tiberius (210 m. below sea level). The average annual precipitation in mm in those areas was, respectively: 120, 900, 478, 553, 500, and 450. The research also found that the average number of Yellowettes per square kilometer in each of the aforementioned areas was, respectively: 27, 92, 953, 380, 773, and 400. In addition, it emerged that during the autumn the amount of Yellowettes dropped in some of the areas. **Task:** Generate a VR to describe the salient trends in the growth of Yellowettes in their natural environment.

Scenario 3 (Poem on Margaret Ann)

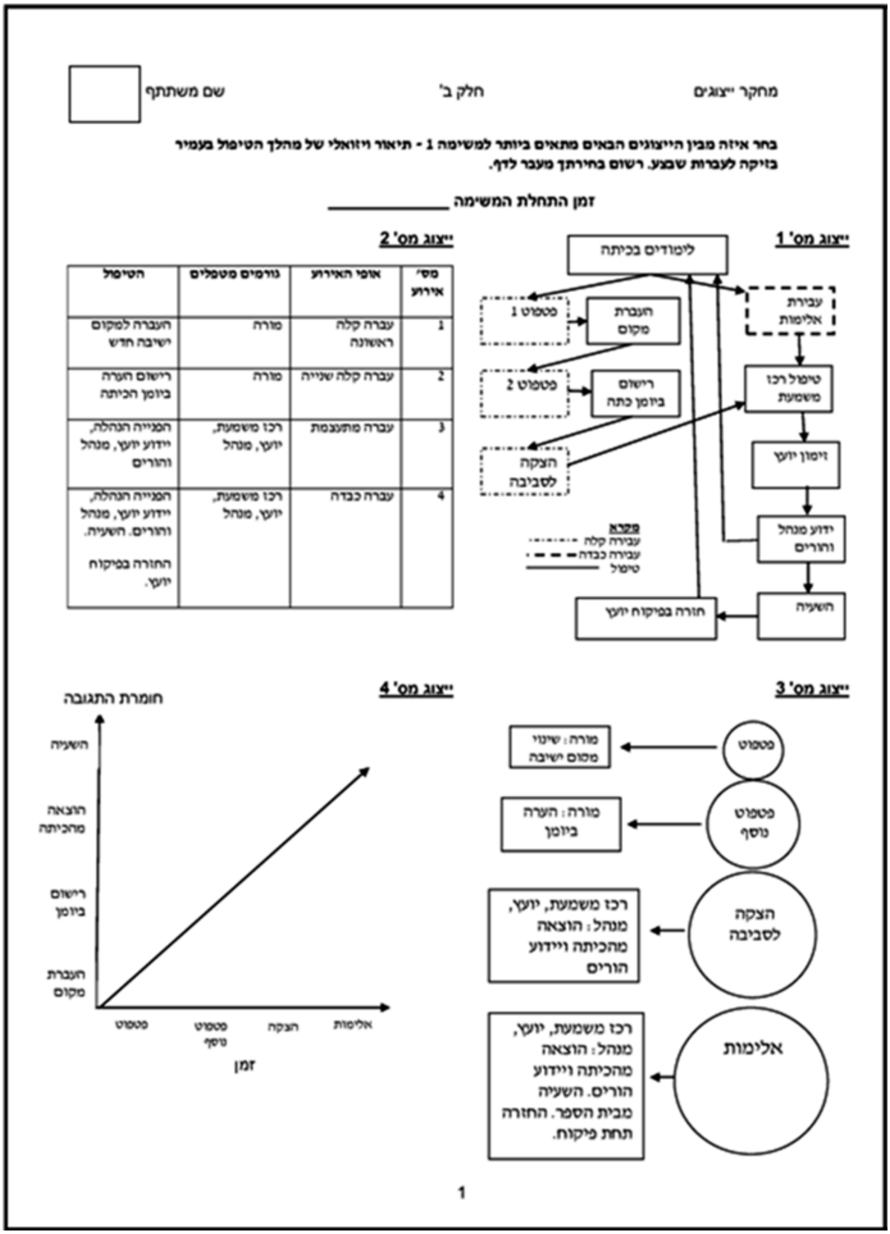
Margaret Ann, a Poem by Nurit Zarchi (1992)

Why always so sad	Yes yes, her dresses straight down
Margaret Ann,	Socks straight up to her knees
The neighbors ask.	The neighbors say.
She seems unhappy	So different, so strange.
Her pale face drawn	
Hair swept into a bun	Did someone abuse her
Yet just a young girl	Without our knowing
She means no offence	Or unable to smile
When replying,	Just born like that
Never a cheeky giggle	Margaret Ann
Yes yes, always respectful.	The neighbors say
Or just withdraws into silence.	Is she really a girl?

Task: Generate a VR to describe the relations between Margaret Ann and the other children.

Appendix B: The Multiple-Choice Task for the Scenarios: Four Ready VRs on Discipline[1]

1



[1] Part B task items are presented to convey readers an impression and layout of each scenario representations.

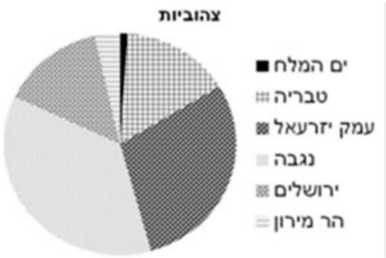
2

מחקר ייצוגים חלק ב' שם משתתף

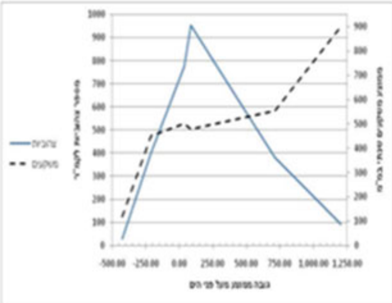
בחר איזה מבין הייצוגים הבאים מתאים ביותר למשימה 2 - תיאור ויזואלי של המגמות הבולטות בגידול הצהוביות בסביבתן. רשום בחירתך מעבר לדף.

זמן התחלת המשימה ______________

ייצוג מס' 1



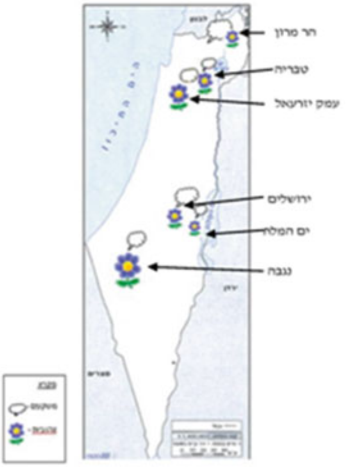
ייצוג מס' 2



ייצוג מס' 3

שם עיר	גובה	צהוביות	משקעים
ים המלח	-424.00	27	120
הר מירון	1202.00	92	900
נגבה	85.00	953	478
ירושלים	713.00	380	553
עמק יזרעאל	35.00	773	500
טבריה	-210.00	400	450

ייצוג מס' 4



1

3

מחקר ייצוגים חלק ב' שם משתתף

בחר איזה מבין הייצוגים הבאים מתאים ביותר למשימה 3 – תיאור וויזואלי של מה שבין מרגרט-אן לילדים אחרים - רשום בחירתך מעבר לדף.

זמן התחלה ______________

ייצוג מס' 1

ייצוג מס' 2

	הילדים	מרגרט-אן
מצב נפשי	*לעיתים עצובים ולעתים שמחים*	תמיד עצובה, לא מאושרת
מראה הפנים	*לא חיוורים, מחייכים*	ארוכים וחיוורים, בלי חיוך
לבוש	*בגדים מקומטים, מרושלים*	שמלות ישרות וגרביים עד הברך
תסרוקת	*פרועה*	שער משוך
התנהגות	*מדברים, לעתים נסים וחוצפנים*	אדיבה תמיד או שותקת אינה חצופה, אינה עונה בגסות
הערכה כללית	*ילדים רגילים*	ילדה אחרת

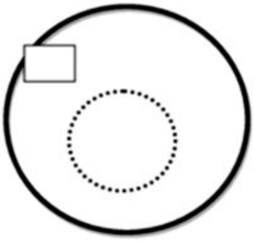
ייצוג מס' 3

מקרא:

הסביבה –

הילדים-

מרגרט-אן



ייצוג מס' 4

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References

Ainsworth, S., & Lowe, R. (2012). Representational learning. In N. M. Seel (Ed.), *Encyclopedia of the sciences of learning* (pp. 2832–2835). New York: Springer.

Baxter, J. A., & Lederman, N. G. (1999). Assessment and measurement of pedagogical content knowledge. In J. A. Baxter & N. G. Lederman (Eds.), *Examining pedagogical content knowledge: The construct and its implications for science education* (pp. 147–161). Dordrecht: Kluwer.

Clement, D. (2013). *Spider/Radar charts*. Retrieved from http://en.wikipedia.org/wiki/Radar_chart

Coll, R. K., & Treagust, D. F. (2003). Learners' mental models of metallic bonding: A cross-age study. *Science Education, 87*(5), 685–707.

diSessa, A. A. (2004). Metarepresentation: Native competence and targets for instruction. *Cognition and Instruction, 22*(3), 293–331.

Gattis, M., & Holyoak, K. (1995). Mapping conceptual to spatial relations in visual reasoning. *Journal of Experimental Psychology of Learning, Memory and Cognition, 22*, 1–9.

Hsieh, H., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative Health Research, 15*(9), 1277–1288.

ilam, B. (2012). *Teaching, learning, and visual literacy: The dual role of visual representations*. New York: Cambridge University Press.

Kagan, D. M. (1990). Ways of evaluating teacher cognition: Inferences concerning the goldilocks principle. *Review of Educational Research, 60*, 419–469.

Korthagen, F. A. J., & Kessels, J. P. A. M. (1999). Linking theory and practice: Changing the pedagogy of teacher education. *Educational Researcher, 28*, 4–17.

Leinhardt, G., Zaslavsky, O., & Stein, M. K. (1990). Functions, graphs and graphing: Tasks, learning and teaching. *Review of Educational Research, 60*(1), 1–64.

Loughran, J., Mulhall, P., & Berry, A. (2004). In search of pedagogical content knowledge in science: Developing ways of articulating and documenting professional practice. *Journal of Research in Science Teaching, 41*(4), 370–391.

Nesher, P., Greeno, J. G., & Riley, M. S. (1982). The development of semantic categories for addition and subtraction. *Educational Studies in Mathematics, 13*(4), 373–394.

Piper, T. (1993). *And there were two. Children and second language learning*. Pippin: Ontario.

Schön, D. A. (1983). *The reflective practitioner: How professionals think in action*. New York: Basic Books.

Shah, P., & Hoeffner, J. (2002). Review of graph comprehension research: Implication for instruction. *Educational Psychology Review, 14*(1), 47–69.

Spiro, R. J., Coulson, R. L., Feltovich, P. J., & Anderson, D. K. (1988). *Cognitive flexibility theory: Advanced knowledge acquisition in ill-structured domains.* Champaign: Center for the Study of Reading, University of Illinois at Urbana-Champaign. (Technical Report No. 441).

Steiff, M., Hegarty, M., & Deslongchamps, G. (2011). Identifying representational competence with multi-representational displays. *Cognition and Instruction, 29*(1), 123–145.

Valentin, J. D., & Sam, L. P. (2004). *Roles of semantic structure of arithmetic word problems on pupils' ability to identify the correct operation*. Retrieved from http://www.cimt.plymouth.ac.uk/journal/valentin.pdf

Wang, X. T. (1996). Framing effects: Dynamics and task domains. *Organizational Behavior and Human Decision Processes, 68*(2), 145–157.

Chapter 4
Slowmation: A Process of Explicit Visualization

John Loughran

Abstract The notion of visualization conjures up an interesting image of what it means to think about teaching science. A concrete approach to supporting teachers' development of their professional knowledge about teaching science through visualization is evident in the use of slowmation. This chapter considers the conceptual basis of slowmation and illustrates how through a process of visualization, images of teaching about science are able to be made both concrete and useable for teachers. The chapter illustrates how, when science teachers introduce slowmation as a teaching procedure, they begin to see into the science concepts they are teaching in new ways. Slowmation creates a working environment in which the teacher is 'forced' to unchunk their knowledge of scientific concepts and begin to visualize the chunks that matter in developing a deeper understanding of the concepts for teaching. As slowmation is conceptualized through the theoretical framework of semiotics, the notion of visualization becomes a helpful way of supporting teachers' active production of their professional knowledge of practice.

Keywords Slowmation • Teaching procedure • Visualization • Introspective visualization • Interpretive visualization • Stop-motion animation • Science • Concepts

4.1 Introduction

Despite the fact that some argue that there is "a pervasive lack of clarity about precisely what constitutes visualization" (Vavra et al. 2011, p. 22), the notion of visualization still conjures up an interesting image of what it means for teaching science.

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Science itself is steeped in a history of the use of models, representations and other forms of visualization crucial to explaining, and illustrating complex, abstract or sometimes unobservable phenomena.

In his review of visualization in mathematics education, Bishop (1989) noted that there are two ways in which visualization has been described: (1) "the what of visualization" i.e., the product, object or visual image; and, (2) "the how of visualizing" i.e., the process, activity or skill associated with visualizing. Further to this, Vavra et al. (2011, p. 22) stated that from their review of the literature that "three important distinctions in the conceptualization of visualization" were apparent. The first was of *visualization objects* (pictures, models, diagrams, geometrical illustrations, simulations, animations, etc.). The second was *introspective visualization* which refers to "mental objects pictured by the mind". The third was of *interpretive visualization* which involves "making meaning from visualization objects or introspective visualizations in relation to one's existing network of beliefs, experiences and understandings". Each of these features has a part to play in developing an understanding of the way in which slowmation (described in detail later in the chapter) can influence students' learning about science and how important visualization therefore is to the teaching of science in schools.

Slowmation (Hoban 2009; Hoban et al. 2011) is an abbreviation of 'slow-animation' and offers a way for students to create their own 'low-tech' animations of science concepts. Slowmation is a digital version of a 'flick/flip book'. A flip book has a series of pictures that vary gradually from one page to the next so that when the pages are quickly turned (flicked/flipped), the pictures appear to move in ways that simulate motion or illustrate changes in a scene (for a detailed history see www.flipbook.info/history.php).

By creating the impression of a moving scene, a flip book becomes a form of animation. Slowmation works in exactly the same way. It is based on taking a series of individual digital photographs and animating them in a simple format by combining them in a sequence known as "stop-motion animation". In terms of the notion of visualization, slowmation comfortably sits in Vavra's category of a visualization object or Bishop's 'what of visualization'. However, as this chapter will illustrate, seeing beyond the object, or product, is important to genuinely understanding the real value of slowmation as a form of visualization; and is all the more important when considering Gilbert's (2005a) compelling argument about visualization playing a central role in science.

Gilbert (2005a) suggested that visualization should be highly regarded in the teaching and learning of science in schools. He was of the view that visualization is a metacognitive skill and that "if visualization is an important aspect of learning – especially in the sciences, where the world-as-perceived is the main focus of interest – then not possessing, having failed to develop, metavisual competence will have serious consequences" (p. 18). This chapter takes up Gilbert's point about the need to further develop students' metavisual competence in school science and does so through a consideration of the nature of slowmation as an important visualization process – both for students' learning of science and for teachers' teaching of science. This chapter examines how, when science teachers introduce slowmation as a teaching procedure, they create new ways of seeing into science concepts. In so doing, they create new opportunities to enhance their professional knowledge of practice.

4.2 Visualization in Science: Informing Approaches to Science Teaching

Visualization in science is well recognized as important with websites devoted to such work designed to engage and entice people to science concepts and phenomena as well as to encourage the production of new and compelling visualization objects (see for example, http://www.sciencevisualization.com/; http://svs.gsfc.nasa.gov/; http://www.wired.com/wiredscience/2012/02/science-visualizations-2011/). However, drawing learners into science through visualization is one thing, incorporating its use in meaningful ways in science classrooms is another; and there are compelling reasons for pursuing it in concerted ways.

Gilbert's (2005b) edited book *Visualization in science*, devotes a section (five chapters in all) to the significance of visualization in science, science education and cognition, thus framing science teaching and learning through the lens of visualization and creating a platform from which an argument about the importance of visualization strongly comes to the fore. For example, Rapp, in his consideration of mental models, drew attention to the place of visualization in science when he noted that:

> Much science involves the explanation of complex, causal relationships in dynamic situations. One line of thinking suggests that only by illustrating these dynamic explanations in a form that captures salient relationships will students understand the complexity (or in some case, the simplicity) underlying a conceptual theory. Also, as some scientific explanations cannot be observed in the everyday world, visualization can provide experience with these concepts … [but] a visualization is by no means a panacea for teaching difficult science topics … [however] three characteristics of learning … specifically relevant to thinking about the design of educationally valid visualizations for science classrooms [are] … First, visualizations are often quite engaging … Secondly, visualizations can be interactive and … interactivity can foster learning through the construction of mental models … Finally, learning is fostered by conveying information in a succinct, guided manner that aligns with the nature of mental representations. (Rapp 2005, pp. 53–54)

There have been studies designed to attempt to determine the extent to which the use of visualization enhances students' learning of science. Cifuentes and Hsieh (2004) in a study with middle school science students, were of the view that visualization should be a focus for curriculum development as a consequence of their exploration of the use of visualization as a study strategy. Clement et al. (2007), using talk aloud protocols with students and experts, concluded that there were observable indicators of the presence of imagery and how it was used in learning and that dynamic imagery from one context could be transferred to a new model being constructed for a new context, thus leading to a deeper level of conceptual understanding. This view is similarly supported by Kuhl et al. (2011) who also concluded that in comparing learning from static as opposed to dynamic visualizations that, although measurable differences in learning outcomes were not evident, that qualitative differences in learning were clear – as a consequence of data (also) from the application of a think aloud protocol. Their major point was that conclusions about learning through visualizations should not be limited to outcome-oriented measures but also to process-oriented approaches that draw attention to learning for understanding as opposed to simple factual recall.

Extending the notion of learning through dynamic visualizations, McClean et al. (2005) developed animations for cellular and molecular processes in order to move beyond the more typical two-dimensional visualization tools. In studying the impact of these dynamic visualizations they found that students who used the animations in addition to traditional teaching, as well as individual study activities, performed better in terms of retention than those who did not use the animations, but also that their understanding of complex systems and processes was enhanced.

> The value of the animations to significantly affect learning suggests … [they are a] major factor in drawing attention to a topic, which in turn acts as a stimulus to transfer the content into working memory … animation and narration lead to deeper learning than a narration in the form of a lecture … animation appears to be an important technology designed to support education. We have already shown that test scores of content material are improved by the use of animations. (pp. 177–178)

McLean et al.'s (2005) work supports views on learning that have been prevalent for some time, as for example Shapiro's (1985) view that learning is enhanced through visualization because visualizers devote more attention to the material being processed. Likewise, Wu et al. (2000) showed how the use of eChem (visualization tool) led to substantially improved learning about chemical representations. However, for many animation programs, the need for computer programs, educational technologies and other complex (and/or expensive) hardware and software demands, has been an impediment to 'classroom take up' despite support for, and advice about, such technologies and the value of their application in school science and mathematics learning (see for example, Thomas 1995).

Some of the reluctance to 'take up' may be linked to teachers' beliefs. Robblee et al. (2000) suggested that teachers' views about how students learn and their perspectives on their own roles impacted their pedagogical decision making and were therefore important when considering the use and value of interactive computer models. Similarly, Hsieh and Cifuentes (2006) noted that although student learning was enhanced through the use of visualization that not all students were happy to use computer assisted visualization techniques and that perhaps such barriers may be linked to individuals' learning characteristics: "15 % of students in the visualization/computer group felt negatively about the use of visualization. They claimed that visualization demanded too much time and effort, and that they needed a teacher's guidance in how to visualize on computers and how to make use of features of drawing and painting tools to generate visual representations of concepts" (p. 144). Addressing these issues in order to assist in visualization is then important if animation is to be a meaningful and helpful learning tool in the ways so often suggested in the literature. As detailed below, slowmation offers such an opportunity and therefore creates pedagogical possibilities for teachers through which visualization in science might be capitalized upon in order to enhance student learning – the pedagogical imperative driving teachers' practice.

4.3 Slowmation

The theoretical framework underpinning slowmation is semiotics – the study of signs and its relationship to meaning making. Peirce (1931), an early leader in the field of semiotics, identified three terms that help to explain how meaning is made when a sign represents an object: (i) an object or referent is the concept or content being represented; (ii) the sign that is created is called a representation; and, (iii) the meaning generated from the sign is called an interpretant. When a representation of a science concept is created using animation, the maker(s) develop meaning from the process because, in the process, they are comparing their ideas with those of the referent or object they are attempting to represent. Such a triadic relationship is dynamic in nature because it involves interaction between the sign or representation (what is created by the learner), the referent (what is being represented) and the meaning made (personal interpretation).

> This three way dynamic relationship between a representation, the object or referent, and its meaning was first illustrated in Pierce's (1931) semiotic triadic model … this semiotic theory for understanding the process of meaning making through creating representations still has currency in science education research … [and as Waldrip et al. (2010) explained] "with any topic in science, students' understandings will change as they seek to clarify relationships between their intended meanings, key conceptual meanings within the subject matter, their referents to the world, and ways to express these meanings" (p. 67). (Hoban et al. 2011, p. 991)

In science classrooms, slowmation can be used to create a working environment that influences not how a teacher might approach teaching a particular concept/topic, but also how a student's learning might be enhanced. Creating a slowmation can help teachers to unchunk their knowledge of the scientific concept/idea under consideration (e.g., particle theory) and begin to visualize the chunks that matter in developing a deeper understanding of that concept for teaching. In implementing slowmation, teachers are placed in a position whereby they begin to confront and manipulate the knowledge that they have, adjust and accommodate that knowledge, and through the visualization (slowmation) begin to recognize specific aspects of their understanding of the concept. Through that process, slowmation helps to make the concept concrete and useable in ways that the literature (above) suggests is important for a teacher to be more informed in working to enhance student learning.

In a project aimed at 'unpacking' the teacher learning process through slowmation with pre-service science teachers (explained in more detail later in this chapter), deeper understandings of teachers' practice and the factors shaping that practice have been studied. Before considering some of those research outcomes, it is first important to understand how slowmation works as a pedagogical approach to science teaching and learning.

4.3.1 Creating a Slowmation

A common and well recognized form of stop-motion animation is "clay animation" (claymation) as used in movies such as Wallace and Grommit and Harvey Krumpet. However, the creation of claymations on a commercial basis are complex, tedious and incredibly time consuming. Therefore the thought of attempting to create three dimensional science models from everyday classroom materials is so daunting that their use as a visualization tool has typically been confined to commercial interests. As a consequence, if they are used, students end up viewing expert-generated animations designed to present science content structured and presented in ways perceived as being helpful for student learning. However, expert-generated animations have their barriers to student learning because they can present key concepts too quickly and as a result, may not explain them sufficiently well for students – usually because they tend to demonstrate concepts in real time: "animations must be slow and clear enough for observers to perceive movements, changes, and their timing, and to understand the changes in relations between the parts and the sequence of events … [they need] to direct attention to the critical changes and relations" (Tvertsky et al. 2002, p. 260).

Clearly, if learners are able to design and create their own animations rather than be passive consumers of information supplied by others (Chan and Black 2005), then they are in a much better position to visualize scientific concepts in ways that would support their learning. Bransford et al. (2000, p. 215) argued that making and manipulating models of concepts is valuable because they "develop a deeper understanding of phenomena in the physical and social worlds if they build and manipulate models of these phenomena." But, as noted earlier, designing and creating animations is typically limited in school science classrooms because the process is usually too complex and/or time consuming. Slowmation offers a way of breaking down those barriers and capitalizing on learning through visualization and encouraging teachers to implement such practices in their science classrooms.

A slowmation is created through a process (see, Hoban et al. 2011, for a full description of the sequence of five multimodal representations) that encourages the 'creator' to think carefully about the concept to be represented so that it can be illustrated in practice through the resulting animation. The first step in the sequence is the research phase through which pertinent information, ideas and understandings of the concept to be demonstrated need to be ascertained and carefully considered. Concepts/themes that involve some form of cycle or sequential change are particularly suited to slowmation, hence mitosis, meiosis, changes in states of matter or life-cycles are common topics. In this research phase, initial questioning of prior knowledge and the information necessary to depict the concept arise as the information and thoughts about how it might best be represented begin to surface. Therefore, visualization of both the referent and representation is initiated. (This aspect of slowmation can be a catalyst for teachers to see beyond content knowledge alone and begin to seriously consider what it is that they know and understand about a concept/topic and how their representation influences their approach to its teaching.)

The second step in the sequence is the storyboard and this places the creator in a position whereby the salient features of the information from the research need to be concretized as representations that might appropriately illustrate the creator's perception of the 'chunks' that "will explain the concept". At this time, questions may arise about whether text, narration or other forms of representation are needed to ensure the slowmation will portray that which the creator visualizes as the major aspects of the concept being illustrated. An important aspect of storyboarding is that it also helps the creator to think carefully about the sequence of events and whether or not the chunks are sufficiently clear and helpful in portraying in a concrete form that which is understood in the mind's eye of the creator. (For teachers, this again creates an opportunity to think about the concept as a learner not a 'deliverer of content' and so continues to challenge the ways in which chunking and representation of ideas impacts approaches to teaching.)

The third step is the creation of models that will be the physical representations of the concept. One reason why slowmation is so appealing is that, as opposed to commercial claymations, sophisticated modeling is not necessary. Clay, playdough, existing models, drawings and other low tech representations are all that is necessary, and the way they are used to create the 'scenes' is by laying them flat on a background in the horizontal plane rather than as self-sustaining creations in the vertical plane. This also allows for the individual changes in the models necessary in creating the digital photographs (next step explained below) to be managed quickly and easily.

The fourth step is the digital photographs. The creation of animation is based on small movements of the models across a number of photographs so that when they are played together they simulate movement. The incremental movement possible in the horizontal plane is simple and efficient and allows for digital photographs to be taken by 'framing' the events from above using a tripod (to hold the camera in place) thus creating the sense of movement within a scene against a consistently framed background. At this step, the storyboard is used to ensure that the script of the slowmation follows the ideas as set out and conceptualized as a consequence of the research and the manner of representation imagined by the creator. Considering the chunking of ideas and information about the target concept (referent) then becomes real and concrete as the imagined process of movement and change is able to be checked against the reality of the design in action. (For teachers, this may well be the first time that their 'mind's eye' visualization of a concept is made concrete for themselves and begins to highlight elements of their own understanding that influence what they might focus more attention on in their teaching of that concept.)

The fifth and final step is bringing the photographs together in a sequence to create the slowmation. Again, because of the low tech nature of slowmation, it is a simple matter of loading the digital photographs into any form of freely available (and typically supplied) movie-maker software on a computer (e.g., QuickTime Pro, MovieMaker, etc.). Having done that, the individual frames are able to be played at a predetermined speed (two frames/second is common, but can be varied dependent on the number of photographs being used and the intended length of the final slowmation) thus creating the slowmation product.

Slowmations have become popular in science teaching at all levels of schooling (for examples, see http://slowmation.com/). However, understanding the real value of slowmation may not always be immediately evident to teachers confused because of that which Appleton (2002) described as a teacher's pursuit of 'activities that work', i.e., the need to have activities that appear fun and keep students busy. Therefore, seeing slowmation through the frame of visualization allows for a deeper understanding of the learning possibilities inherent in slowmation (as both a process and a product) and captures the learning aspects important to meaning making (i.e., interpretant).

4.3.2 Slowmation: Multiple Forms of Visualization

As noted earlier in the chapter, visualization has been described as encompassing two important aspects – the 'what' and the 'how' (Bishop 1989). It is not difficult to see the 'what' of slowmation as there is a clear product (the animation created) which also equates with Vavra et al.'s (2011) notion of a visualization object. The 'how' though needs more careful consideration as it touches on the other two aspects that Vavra et al. described, that of *introspective visualization* (mental objects pictured in the mind) and *interpretive visualization* (making meaning from visualization objects or introspective visualization of existing networks of beliefs, experiences and understandings). The next section explores these aspects of visualization in relation to both the product and the process of slowmation.

4.3.3 Slowmation as a Product

Slowmation as a product is a low tech animation. It is easily created and is an engaging, creative and enjoyable task for students. However, just as Linn et al. (2006) noted in their description of TELS (Technology Enhanced Learning in Science), so too slowmation needs to be understood as valuable because it "enable[s] students to connect scientific visualizations to their understanding of complex scientific ideas [and] help[s] guide students to make sense of visualizations rather than viewing them as amusing movies" (p. 1050). Slowmation is able to do this because beyond constructing the (simple) physical models and contextualizing them within a background (scene), there is also the need to manipulate the objects in order to, through the individual photographs taken of the incremental changes being performed, create the illusion of movement. When all of the photographs are combined in sequence, the animation comes to life and a clear product becomes immediately tangible.

At the simplest level, slowmation visually represents the idea/concept (referent) under consideration as conceptualized by the author. However, that product can be enhanced through the addition of narration, the use of music, signs, symbols, text or messages, or more sophisticated forms of display (e.g., moving from two-dimensions to three-dimensions and/or the use of commercial models and more complex approaches to depiction). But the important point is that the 'control' of development and depiction rests with the author – an important element of meaningful learning – and something that encourages teachers to pursue student centred learning in their science classrooms.

A valuable feature of slowmation is the combination of two forms of visualization: the individual photograph(s); and, the development of a 'movie'. From the storyboard that sets out the plan for the slowmation, a number of scenes are depicted and so, in one sense, the storyboard is a big picture overview that comprises a number of visual representations (each scene in the storyboard). These scenes can be regarded as individual representations which depict the author's perspective on the particular features of the concept/theme/process under consideration and how they come together to illustrate the author's conceptualization of the idea as a whole. As static constructs the storyboard scenes convey the author's understanding of the data (e.g., elements, phases, aspects) that comprise the concept attempting to be portrayed. That static form is transformed when each scene is brought to life through the expansion via the individual frames (photographs) necessary to simulate movement using the models. Hence the slowmation itself leads the author to change a static visualization (storyboard) into an interactive visualization – which is dynamic as a consequence of the data sequencing across changing scenes – creating time lapse from once individual static objects.

> … computer-based visualization appears to be particularly well suited to visualization for understanding. This is so because the computer lends itself so naturally to representations with text, sound, and visual displays. The possibility of combining language and a dynamic visual display while allowing for the user to control speed and other presentational factors underwrites much of the current enthusiasm for computer-based visualization. (Phillips et al. 2010, p. 81)

The change from a static to interactive visualization illustrates a transformation of data from an abstract to a concrete representation; the success of that transformation is often dependent on the extent to which the 'data changes' adequately capture and portray the 'markers' anticipated by the author as conveying particular meaning (initially for the author in conceiving the slowmation but ultimately for the audience when viewing the final product). In terms of visual representation, it is not only the model(s) but also the background that helps in cueing the viewer to intended features for more focused attention. Hence, such things as colour (in models and background) impact a viewer's attention and can enhance recognition and visualization of data; especially so as changes in scene and various markers emerge through the movements depicted when brought to life through the movie itself.

The effectiveness of the illusion of movement created through taking the static photographs and combining them in sequence is influenced by the number of frames (incremental changes) and the speed with which the frames are viewed. As noted earlier, two frames/second is the common form used for slowmation, and the rate of data flow (speeding up, constant rate, slowing down) can be important in further portraying the concept under consideration and attracting the viewer's attention to particular features of the slowmation. Through the use of narration and/or annotation, the viewing experience may be enhanced as different elements of the visualization emerge across the time sequence and are visually cued to aid interpretation and understanding of that which is being depicted.

As all of the above suggests, although thinking about slowmation as a product might initially appear to be a simple way of conceiving of it as a visualization tool, for the author, there are a multitude of decisions and possibilities inherent in constructing the product as the original abstract conceptualization of the animation and the concrete form of product are compared and contrasted. As opposed to more sophisticated commercially developed animations constructed by experts for students to watch, slowmation allows multiple points of learning for the author as the actions of designing, constructing, creating and displaying all invite creativity and innovation through the direct control possible in the process of developing and refining the author's personal final product. When teachers understand these crucial underpinnings of slowmation, the importance of the teaching-learning relationship becomes all the more real and the superficial view of slowmation as 'an activity that works' is able to be challenged in meaningful ways.

Slowmation as a product is obviously a valuable visualization tool because it offers a depiction of the author's understanding of the concept under consideration in a tangible fashion through the nature of the narrative being displayed through the final product. Learning from the product is then available to an individual audience (the student-author and the teacher) and collective audience (class as a group). Learning though is not limited to the notion of slowmation as a product, there are many interlinked processes within design and construction that contribute to this form of visualization being educative at a number of levels; all of which impact teachers' understandings of their practice, the way it is structured and the influence it might have on students' learning.

4.3.4 Slowmation as a Process

> Science education is a domain in which teaching methodologies have often relied on matches between learning activities (i.e., external presentations) and the knowledge we wish students to acquire from their lessons (i.e., internal representations). Lab-based activities, active learning assignments, and task-driven coursework all help students learn about scientific topics through active participation rather than passive viewing or listening. External representations ('visualizations') have emerged as a methodology that, in many ways, relies on similar principles to facilitate learning. A visualization can be thought of as the mental outcome of a visual display that depicts an object or event … the need to assess the effectiveness of 'visualizations' in science classrooms has led to increased interest in the impact of their use. (Rapp and Kurby 2008, p. 30)

An important aspect of developing a slowmation revolves around the nature of the knowledge to be represented. Typically in the teaching of science, the teacher is perceived as knowing the subject matter content (breadth and depth) in ways that goes beyond that of the majority of students in their class and so the archetype of science as the delivery of propositional knowledge routinely arises. However, another way of thinking about this situation is that teachers may have become so comfortable with their understanding of the subject matter knowledge, that the manner in which they have 'chunked' (White 1989; White and Gunstone 1992) that information masks the complexity and intricacy of what it takes to assemble the ideas in a coherent way for learning in order to better understand the idea as a whole. Therefore, the teacher has fewer (but larger and richer) chunks of knowledge on the topic (e.g., particle model as an all-encompassing way of understanding states of matter) than students who may have numerous smaller, less connected and poorly integrated chunks that they might struggle to bring together in a coherent way (e.g., if solids, liquids and gases are only propositional knowledge it can be challenging for a student to make sense of such things as sublimation or colloids). Therefore, the nature of the representations that teachers carry (and/or construct), influences their understandings of subject matter knowledge, and the nature of their chunking inevitably influences the complexity of the representations they need to illustrate their understanding; which inevitably impacts the manner in which they teach those ideas.

As noted earlier, the first phase in developing a Slowmation is that of research: researching the topic/theme under consideration. For a teacher, this step encourages them to tap into students' prior knowledge and how it is influences (or not) their developing understanding of the topic. Through this process, students are not controlled or bound by the teacher's chunking but are open to various forms of chunking from the different sources on which they draw – something which through didactic approaches is often difficult to achieve. The process then encourages the development of representations that aids in knowledge building and is not only open-ended but also derived of a sense of creativity and innovation – two highly prized features of learning that teachers often consider difficult to encourage and support through 'typical' approaches to science teaching.

Storyboarding is a process that encourages, questioning of the referent and the representations (individually and as a group) as consideration of the congruency between mental models and anticipated products acts as a key organizing principle. Refining the storyboard is an active process through which the synchronization of movement and the chunking through scenes offers feedback about the adequacy of the representation as a coherent whole. This process is further reinforced when the storyboard is 'made real' through the development and use of the models that comprise the third phase of Slowmation production. Again, comparison between that which was envisaged and the physical representation created through the models is able to be compared to the understanding of the referent (idea/concept/theme) from the author's perspective – thus giving a teacher an ability to see into students' developing understanding of the concept in ways that allows prior knowledge to be recognized and challenged in less threatening ways than public classroom questioning.

The fourth phase of slowmation is taking the digital photographs of the incremental changes made with the models as the static forms become dynamic. Through the simulation of change over time, an overall understanding of the referent is able to be tested in ways that encourage the author to consider not only the chunks that are captured and portrayed in each scene, but also the overall adequacy and accuracy of the depiction of the temporal dimensions conceived through the introspective visualization that is at the heart of the process as a whole. Importantly, this aspect of slowmation then allows teachers to see that learning goes beyond the much bemoaned 'school science learning' as the student is genuinely shaping, challenging and constructing conceptual knowledge in ways that are very different from 'guess what's in the teacher's head' depictions of school science.

The fifth and final phase of constructing the slowmation is downloading the digital photographs then uploading them into a movie-maker program to turn the still photographs into an animation. At this stage, interpretive visualization comes to the fore as existing understandings are confronted as a consequence of viewing the slowmation and considering how it depicts, negates or challenges the conception of the referent. Thus meaning making (interpretant) is likely to be catalyzed as there may be satisfaction with the product, or a desire for further refinement to better align the product with the prevailing mental images of the referent. Again, for a teacher, this phase offers something very different to typical science classroom practice, satisfaction/dissatisfaction with the product is driven by students' understandings not imposed by a teacher's directive.

As this section highlights, product and process come together to encourage learning through visualization in ways that are based on independent and active learning but are fundamentally driven by slowmation as a valuable pedagogical tool. How teachers understand these elements of slowmation and how that understanding impacts their practice is considered in the next section of this chapter.

4.4 Understanding Slowmation: A Teacher's Perspective

As the above suggests, understanding Slowmation as visualization involves a process of representation, deconstruction and reconstruction, in order to examine the nature of the science concept (referent) under consideration.

Keast et al. (see, 2009, 2008) conducted a series of studies with pre-service science teachers designed to examine how beginning teachers came to understand the value of slowmation as an approach to science teaching and learning and how that impacted their practice. Data from those studies was drawn from many sources including interviews about their experiences of learning to do slowmations, teaching using slowmation and evaluating their students' learning from making slowmations.

The research was conducted in a preservice science teacher education program qualifying students to teach General Science at the secondary level (Years 7–10; students aged 12–16). Preservice teachers entering the program had either an undergraduate qualification and were therefore completing the fourth year of a Bachelor of Education double degree (e.g., B.Sc./B.Ed.) or were post graduate students completing the 1-year end-on Postgraduate Diploma in Education (Grad. Dip. Ed.).

Data collection was based on three aspects of participants' experiences with learning about, and using, slowmation. The first was in creating their own representations of particular science concepts through their own slowmations (in small groups, 3–4 participants) and discussion of the process with their peers. The second was derived of participants' presenting and reviewing with their peers the slowmations their students constructed when these teachers taught using slowmation as a pedagogical approach in their science classes. (Data for both of these aspects was collected through audio recording and video recording group work, presentations, reviews and discussions). The third aspect involved participants' reflections on their learning as a consequence of the first two aspects with a particular focus on the impact that learning had on their thinking about their science teaching (data for this aspect included semi-structured interviews with volunteers at the end of their program).

The following section considers indicative data from these projects designed to illustrate participants' experiences in learning about and teaching using slowmation.

4.4.1 Learning About Slowmation

It is well recognized that in order to understand an approach to teaching, it is helpful to experience that approach as a learner. Slowmation is a good example of an approach that, once it has been experienced as a learner, creates a greater sense of confidence in being able to implement it as a teacher and to grasp the pedagogical underpinnings of the approach. The data drawn from the slowmation projects presented in this chapter generally support the view that making a slowmation before attempting to teach using slowmation is important as stated by Sarah.

> It's different doing slowmation [yourself] than actually teaching it with your class, [not doing it myself] what would have put me off … I wouldn't have felt confident. (Sarah)

As noted earlier, all participants created their own slowmations in small groups and considered their learning from that process as important in shaping in their understanding of the structure of the procedure.

> I thought it was good that we were able to do our own [slowmation] because it kind of, you know, got us used to making it and how to put it onto the computer … and we knew if we had any problems we could [get help] so I think that was good [doing that]. (Sue)

Concepts/topics selected by participants were those that they had been teaching in schools and were commonly listed in curriculum documents (e.g., DNA replication, Day and Night, Photosynthesis, Solar system, States of Matter, Life cycles, Chemical reactions, etc.). However, despite participants' perceived knowledge of the topics, doing a slowmation highlighted their need to think beyond the content alone.

> Ah, I needed more practice with it before implementing it … more practice in making more slowmations, not just myself making them but actually presenting the concept … until I actually tried it I wasn't really sure what were the key things, I had no idea what the most important components of a slowmation were. (Wayne)

In making a slowmation, a teacher becomes attuned to key technical and pedagogical issues for using slowmation that might otherwise not be so clear. On the surface, slowmation can appear to be technically challenging and time consuming, both of which can be barriers to implementation. Participants were conscious of these issues and consistently raised them as difficulties that might impact at the personal as well as the curriculum level.

> … all these computers and laptops and digital cameras which I'm probably not [so good with] I thought, "oh my gosh what am I going to do if I get into the classroom" I didn't even know how [I'd do it] … (Sue)
>
> I really liked it but I thought it took a lot of time to set up and get going in class, it might be a bit too long for some units and schools, it takes a lot of classes to do and some people might think that it's, you know, they could do other things that are shorter and might achieve the same result or something similar. (Ellen)

For the large majority of participants, despite their recognition of the likely 'pitfalls' in teaching using slowmation, they were enthusiastic about that which was achieved when they implemented the procedure in their science classes as illustrated in the next section of this chapter.

4.4.2 Teaching Using Slowmation

As noted earlier, slowmation could easily be viewed as a fun activity. However, when teachers observe their students' carefully whilst constructing their slowmations much more emerges about the nature of their learning than superficial views of fun or hands on activities. Much of the learning is driven by two important aspects of teaching, the first is the move away from teacher dominated practice, "it was a lot more student driven which I really enjoyed as a teacher because you know the students don't like a teacher up there dominating the class all the time" and the second is offering students genuine opportunities to pursue their own understanding and to capitalize on the questions created in their own minds through visualization as both a process and a product.

> Kids learn in different ways, kinaesthetic modelling is a really good way of learning in science rather than just seeing a diagram or a series of steps or something, slowmation is a good way of showing you how something happens … that the diversity of thinking and kids need to have that ability to work on different tasks and different projects, it has a lot to do with the visual aspect and actually doing something, actually seeing the thing happen, actually seeing the process on the screen was good for all the students not just the ones who made it. We had their movie moment where we showed all of them [slowmations] and discussed them and that sort of thing and that helped the whole class, not just that small group. (Ellen)
>
> Interviewer: You mentioned before that you saw something in the class where 'they didn't understand that before' …
>
> Sarah: Yeah, one of the boys, they were doing levers and they did one on different types of levers and there were speed multipliers and force multipliers and I think when he was actually in the group he didn't understand the difference between what a speed multiplier did and what a force multiplier did but there were 2 other boys in his group that really grasped that concept and so they did one with a tennis ball I think, and for a speed multiplier the tennis racket hitting the ball and I can't remember what they did for a force multiplier but anyway when we actually came back to watch it I could tell that he didn't really understand it, so we started

talking about it a little bit and then you know, he said he got it but then I think the light bulb moment for him was when we started watching back the other videos and we started going through examples of what a speed multiplier was and a force multiplier and he was like, "oh I understand it now!" and then because we'd watched it [he got it] … and then a couple of lessons later we watched his video again and he's like, "now I understand how that acts as a force multiplier and that acts as a speed multiplier" and I think for him because he wasn't strong in science at all he was like, "wow I actually learnt something" and he'd never passed a science test before … he's like, "normally we just sit down and write things in our text books and learn science from doing experiments." [He normally] doesn't understand [science], but slowmation actually, like using the technology and the plasticine, making it actually helped him understand what he was learning.

As the quote above suggests, slowmation offers teachers new ways to see into, and respond to, students' developing ideas of concepts. In particular, it is helpful for drawing attention to alternative conceptions in new ways. Loughran et al. (2012) examined how teachers became more sensitive to students' alternative conceptions when using slowmation. They explained the uncovering of these as being catalyzed in two ways. The first was through the learning as a consequence of the classroom presentations of students' slowmations – teachers began to recognize alternative conceptions in their students' finished products. The following transcripts from a discussion by preservice teachers following viewing their students' slowmations illustrates this first point.

Lecturer: So what are they showing here?

Participant 15: Oxygen

Participant 12: Watering

Participant 17: And water into the leaves, which is a bit of a misconception as in it's brought up through the roots not into the leaves.

Participant 18: I think they're bringing the water through the veins of the leaf rather than carbon dioxide and oxygen just coming out of the green parts.

Lecturer: Yeah it's a bit hard to know isn't it? This is where you might want them to explain it.

Participant 19: They're not saying what the sun's doing there apart from looking pretty.

Participant 20: And what's the major alternate conception that they miss here? 'Cos in primary school the major thing that they're learning, the major alternative conception with plants is that they don't realise that plants respire. You know 'cos plants photosynthesize and respire … and that's the number one alternative conception and they don't show that at all do they?

Lecturer: The light and dark reactions

Participant 19: … instead of respiration?

Participant 20: Plants do both at the same time the thing is though that they photosynthesize more than they respire and that's one thing that they're not showing here and so they've actually got an alternate conception.

Participant 3: And most alternative conceptions cannot be spoken through so you'll find that you cannot debunk an alternative conception by speaking to it and that's the number one thing. How do you 'break' an alternative conception? Because you've got to remember that these students have had a lifetime of thinking this way or if they've learnt something they've got it from what they consider a legitimate source, text book or something like that, and you in 2 seconds cannot break that.

The second way that they came to recognize and respond to alternative conceptions was through the careful observation of their students' thinking and 'chunking' through their story boards. Commonly, the participating teachers came to see that simply telling their students about a concept did not necessarily alter their thinking about the concept in any appreciable way. Hence, through using slowmation, these teachers were personally confronted by the limitations of transmissive approaches to teaching and developed a greater sense of the value of creating conditions to help students confront their own thinking in productive ways. They began to implement different ways of responding in their practice beyond simply restating the facts.

> In the chunking sheet yeah, I didn't actually say that's a misconception, I didn't want to say you know, "that's wrong" so I just said you know, have you ever thought about that, maybe this could be done in this way and they would be like, "oh ok maybe" and I said "look in your text books and see what that says" I didn't want to take it up and be like "that's wrong, fix that up" it was kind of like, "have you thought about this? What do you think?" I wasn't going to give them the answer I gave them the opportunity … still if they were adamant that that's what it was, that was ok for them … It wasn't about me saying "that's wrong, your slowmation has to be perfect". (Sarah)
>
> Interviewer: So do you mean would you use the chunking sheets without making the movie?
>
> Sharon: Um, I think, I would if there was an idea that a lot of students were a bit mixed up or there seemed to be a bit of like one student believed this but then another student believed this so I think there would be another form of assessment of students' beliefs or misconceptions and then going to a chunking sheet, using that and then getting them to clarify their ideas again. So yeah I think you could probably use it without making the movie … it points out if there are any misconceptions because they're putting their own ideas on to the paper and as I said I collected them after the first one and I was looking at them and I have to say the ones I did most of them were pretty spot on with their ideas. But it allowed me to look at them and go, "ok this student here has got this idea a little bit confused" so maybe [I'd] speak to them you know highlight, "maybe include this information" or "this isn't quite correct" and then I think getting the students into groups and doing the same process and making another big group chunking sheet was good because each of the different students had maybe one little [bit of an idea] and extra step, or they've included a little bit more information to this part and I think that was good that it allowed other students to go, "Oh ok, I didn't think of that" and then they could build on each other's ideas as well.

4.5 Conclusion

Through the theoretical framework of semiotics, slowmation illustrates well how the notion of visualization is helpful in understanding the ways in which slowmation can enhance students' science learning as a consequence of it being thoughtfully implemented in a teacher's science practice. As I trust this chapter illustrates, understanding slowmation as an important pedagogical visualization tool can be a catalyst for teachers to become more informed about science teaching and learning.

As the chapter attempts to make clear, that which a science teacher can see and learn from both the process and the product of slowmation offers insights into the value of visualization and draws serious attention to why an explicit focus on visualization in teaching and teacher education is helpful. At a time when science teaching and learning is increasingly questioned, criticized and scrutinized as a consequence of national and international testing regimes (e.g., TIMMS, PISA, ROSE), it is important to be reminded of the pedagogical underpinnings of practice that are crucial for valuing science teachers' professional knowledge of practice. Slowmation offers a way to help teachers work with scientific concepts so that students internal representations can become public. As Gilbert suggests, "It is entirely possible that, once a series of internal representations have been visualized, that they are amalgamated/recombined to form a novel internal representation that is capable of external expression" (Gilbert 2008, pp. 4–5). I think it is fair to suggest that Slowmation does that, and does so in a creative and engaging way.

References

Appleton, K. (2002). Science activities that work: Perceptions of primary school teachers. *Research in Science Education, 32*(3), 393–410.

Bishop, A. J. (1989). Review of research on visualization in mathematics education. *Focus on Learning Problems in Mathematics, 11*(1–2), 7–16.

Bransford, J. D., Brown, A. L., & Cocking, R. (Eds.). (2000). *How people learn: Brain, mind, experience and school*. Washington, DC: National Academy Press.

Chan, M. S., & Black, J. B. (2005). *When can animation improve learning? Some implications for human computer interaction and learning.* Paper presented at the proceedings of world conference on educational multimedia, Hypermedia and Telecommunications 2005 (pp. 2581–2588), Norfolk.

Cifuentes, L., & Hsieh, Y.-C. J. (2004). Visualization for Middle School Students' engagement in science learning. *Journal of Computers in Mathematics and Science Teaching, 23*(2), 109–137.

Clement, J., Zietsman, J., & Monaghan, J. (2007). Imagery in science learning in students and experts. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 169–184). Dordrecht: Springer.

Gilbert, J. K. (2005a). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 9–27). Dordrecht: Springer.

Gilbert, J. K. (Ed.). (2005b). *Visualization in science education*. Dordrecht: Springer.

Gilbert, J. K. (2008). Visualization: An emergent field of practice and enquiry in science education. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 3–28). Dordrecht: Springer.

Hoban, G. F. (2009). Facilitating learner-generated animations with slowmation. In L. Lockyer, S. Bennett, S. Agostino, & B. Harper (Eds.), *Handbook of research on learning design and learning objects: Issues, applications, and technologies* (pp. 313–330). Hershey: IGI Global.

Hoban, G. F., Loughran, J. J., & Nielsen, W. (2011). Slowmation: Preservice elementary teachers representing science knowledge through creating multimodal digital animations. *Journal of Research in Science Teaching, 48*(9), 985–1009.

Hsieh, Y.-C. J., & Cifuentes, L. (2006). Student-generated visualization as a study strategy for science concept learning. *Educational Technology & Society, 9*(3), 137–148.

Keast, S., Cooper, R., Berry, A., & Loughran, J. J. (2008). *Slowmation: Learning about teaching science*. Paper presented at the Australasian Science Education Research Association, Brisbane, Australia.

Keast, S., Cooper, R., Berry, A., Loughran, J., & Hoban, G. (2009). *Slowmation as a pedagogical scaffold for improving science teaching and learning*. Paper presented at the American Educational Research Association, San Diego.

Kuhl, T., Scheiter, K., Gerjets, P., & Gemballa, S. (2011). Can differences in learning strategies explain the benefits of learning from static and dynamic visualizations? *Computers & Education, 56*(1), 176–187.

Linn, M. C., Lee, H.-S., Tinker, R., Husic, F., & Chiu, J. L. (2006). Teaching and assessing knowledge integration in science: Interactive visualizations combined with online inquiry and embedded assessments can deepen student understanding of complex ideas in science. *Science, 313*(5790), 1049.

Loughran, J. J., Berry, A., Cooper, R., Keast, S., & Hoban, G. (2012). Preservice teachers learning about teaching for conceptual change through slowmation. *Asia Pacific Forum on Science Teaching and Learning, 13*(1), 1–12, http://www.ied.edu.hk/apfslt/v13_issue1/foreword/

McClean, P., Johnson, C., Rogers, R., Daniels, L., Reber, J., Slator, B. M., & White, A. (2005). Molecular and cellular biology animations: Development and impact on student learning. *Cell Biology Education, 4*(2), 169–179.

Phillips, L. M., Macnab, J. S., & Norris, S. P. (2010). *Visualization in mathematics, reading and science education*. Dordrecht: Springer.

Pierce, C. (1931). Logic as semiotic: The theory of signs. In B. Justus (Ed.), *Philosophical writings of Peirce (1893–1910)* (pp. 98–119). New York: Dover, Reprint 1955.

Rapp, D. N. (2005). Mental models: Theoretical issues for visualizations in science education. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 43–60). Dordrecht: Springer.

Rapp, D. N., & Kurby, C. A. (2008). The 'Ins' and 'Outs' of learning: Internal representations and external visualizations. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 29–52). New York: Springer.

Robblee, K. M., Garik, P., Abegg, G. L., Faux, R., & Horwitz, P. (2000). *Using computer visualization models in high school chemistry: The role of teacher beliefs*. Paper presented at the American Educational Research Association, New Orleans. http://search.proquest.com/docview/62424147?accountid=12528

Shapiro, M. A. (1985). *Analogies, visualization and mental processing of science stories*. Paper presented at the Information Systems Division of the International Communication Association, Honolulu. http://search.proquest.com/docview/63387340?accountid=12528

Thomas, D. A. (1995). *Scientific visualization in mathematics and science teaching*. Charlottesville: AACE.

Tvertsky, B., Morrison, J., & Betrancourt, M. (2002). Animation: Can it facilitate? *International Journal of Human-Computer Studies, 57*(4), 247–262.

Vavra, K. L., Janjic-Watrich, V., Loerke, K., Phillips, L. M., Norris, S. P., & Macnab, J. (2011). Visualization in science education. *Alberta Science Education Journal, 41*(1), 22–30.

Waldrip, B., Prain, V., & Carolyn, J. (2010). Using multi-modal representations to improve learning in junior secondary science. *Research in Science Education, 40*(1), 65–80.

White, R. T. (1989). *Learning science*. Oxford: Blackwell.

White, R. T., & Gunstone, R. F. (1992). *Probing understanding*. London: Falmer Press.

Wu, H.-k., Krajcik, J. S., & Soloway, E. (2000). *Promoting conceptual understanding of chemical representations: Students' use of a visualization tool in the classroom*. Paper presented at the National Association for Research in Science Teaching, New Orleans. http://search.proquest.com/docview/62315486?accountid=12528

Chapter 5
Secondary Biology Teachers' Use of Different Types of Diagrams for Different Purposes

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Abstract This study presents various ways in which secondary biology teachers incorporated diagrams in their classroom teaching. To understand biology teachers' instructional use of diagrams, classroom observations were conducted in one state senior high school in Western Australia. A total of 120 lessons in Grades 9–12 taught by five biology teachers were analyzed to produce three assertions that illustrate the instructional practice of using diagrams in secondary biology classes. The research has demonstrated a variety of different ways that experienced biology teachers used diagrams in their teaching to engender student interest and understanding of biological concepts. These findings can be used to help other biology teachers develop a better understanding of the different roles and functions of different types of diagrams in teaching biological concepts.

Keywords Biology • Visual representations • Iconic representation • Schematic representations • Symbolic representations • Diagrams • Charts • Graphs • Instructional practices • Photographs • Analogic explanations

5.1 Introduction

In teaching and learning of science, we frequently use diagrams. There are numerous images, photographs, schematic diagrams and naturalistic drawings on each page of biology textbooks and they are a big part of teachers' classroom instruction (Pozzer and Roth 2003; Roth et al. 1999). Such frequent use of diagrams is not just because they are a nice visual addition to textual explanation of

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science concepts, but because they are an integral part in constructing and communicating scientific facts and processes (Lynch 1990). Scientific diagrams are often the results of a careful process of selecting, enhancing, and connecting particular aspects of a scientific phenomenon, and they can communicate the concepts in their own elaborate ways (Lynch 1990). However, interpreting scientific ideas through diagrams is not as simple as we often think. Using diagrams to learn science effectively can be challenging for students. For example, Novick (2006) has found that in order to understand what diagrams represent, students need sufficient knowledge in both scientific content and diagrammatic conventions. As cognitive research continues to explore the complex processes by which people learn with visual representations, we as educational researchers investigated how visual representations are actually used in school settings for teaching and learning (Gilbert 2008; Kozma 2003). Are there any particular ways in which teachers adopt diagrams to support students' learning and communication of science? If so, do teachers' strategies differ depending on the type of diagrams and the science content? In this chapter, we describe some of secondary biology teachers' teaching strategies of integrating diagrams in relation to the types of diagrams.

In identifying different types of diagrams, we relied on Hegarty et al.'s (1991) classification: iconic diagrams, schematic diagrams, and charts and graphs. Iconic diagrams are realistic pictures or drawings of concrete objects. They have similar appearance and structure to what they represent, and they are effective in comparing the differences between various species or helping students visualize the things that are not readily available to the naked eyes (Hegarty et al. 1991; Novick 2006). Compared to iconic diagrams, schematic diagrams are rather abstract representations, such as electric circuit diagrams or phylogenic trees. They often contain simplified/modified information of a complicated system to highlight the main messages of the diagram, and they may not have a good spatial correspondence to what they represent (Novick 2006). Consequently, interpretation of a schematic diagram requires learners to decipher the abstract content of the diagram and make a connection to the target concept. The third category, charts and graphs, presents the relationships of quantitative data. For example, a line graph can display the change in human population over the years, and a pie chart can show the percentage of oxygen in air. It is often necessary for the reader to identify all independent variables before making an interpretation because abstract meanings and numerical data are embedded into charts and graphs.

This study builds on these three diagram categories in an attempt to describe and analyze how secondary school biology teachers use these diagrams to introduce, explain and evaluate biology concepts, many of which are abstract. This research does not measure the frequency of diagrammatic usage, but examines how and why teachers use particular categories of diagrams when they are teaching specific areas of biology. In the process of diagram-inclusive instructional practice, the specific diagrams used are discussed.

5.2 Methods

With regards to the use of diagrams in the classroom, the authors adopted a qualitative research design (Erickson 1986), drawing primarily on observations of biology teachers' instruction. The first author observed biology classes for 7 months as a non-participant observer while the second and third authors guided the observations and the analysis. The researchers did not intervene in the classroom so that the teaching was completely in the control of the teachers. Field notes were taken throughout the observation period to examine how different types of diagrams were used in secondary biology teaching, and occasionally, certain classroom activities were audio-taped to keep a detailed record of the class interactions with diagrams. In order to grasp the nature of practices in the classroom, the researcher used specific instances as references for subsequent observations (Merriam 1998). The researchers reviewed the data corpus and made tentative assertions. After additional data collection and further discussion, the researchers reached the final assertions as presented in this chapter (Erickson 2012).

We chose five teachers based on their biology expertise, experience in teaching, level of integration of visual media into their teaching, and willingness to have the researcher in their classroom over a prolonged period. The teachers, who taught classes in Grades 9–12, are identified as Mr. Kimbley, Mr. Dandridge, Mr. Barwick, Mr. Cobbs and Mr. Stradford. A total of 120 lessons from five biology teachers were observed. A variety of biological topics were taught by the teachers, including conditions of living organisms, population variation, gas exchange in plants, the nervous system, the cardiac cycle, and human respiratory system.

5.3 Findings

From an analysis of the lessons observed, three assertions were identified. The first assertion is concerned with teachers' choice of iconic diagrams when beginning a biology lesson and how they are used them to introduce a concept. The second assertion is about how teachers choose different diagram types to explain information across different representational levels and how this information was used to assess students' learning outcome. The third assertion emphasized the analogical features of diagrams in representing scientific information. These assertions generated by the classroom observations provided a view on understanding how different types of diagrams were used in secondary school biology teaching.

Fig. 5.1 A photo of a creek to introduce the concept of the living conditions (This photo was taken from Wikipedia Commons with the Creative Commons Attribution-Share Alike 2.0 Generic license)

5.3.1 Assertion 1: Teachers Used Iconic Diagrams to Introduce the Context and Explain a New Topic

The first step for comprehending diagrams and text always involve selecting relevant features of representations for further processing (Mayer and Moreno 2003). In early stage of instruction of the content, biology teachers often guided students to recognize the topic by introducing an iconic diagram and discussing some features of the diagram. Showing iconic diagrams not only worked as background knowledge contexts, but also as an advance organizer to help students to have a clearer focus on the content.

5.3.1.1 Conditions of Living Organisms

Previous research has found that for student knowledge growth, it is necessary for learners to be able to combine multiple representations into integrated knowledge structures. However, before that, learners have to select what they perceive to be the most relevant aspects for further processing (Cook et al. 2008). Students' attention may need to be directed into perceiving what would be the topic of the lesson, and the process of extracting relevant information might draw heavily upon the first representations provided by the teacher prior to any formal teaching.

While introducing the content of *Conditions of Living Organisms*, Mr. Kimbley showed a photograph of a creek with clean running water using the PowerPoint slide shown in Fig. 5.1. He then asked students questions like "Where are we? …

What can you find from this picture?" "Water … a river" one student responded. Though most students remained silent in response to this simple question, everyone seemed to have reached a consensus about the teacher's question. Students' attention had therefore been concentrated on the image of the river or the water environment as the target information, not only because the running river is located in the center but also the entire photograph implied that subsequent teaching and learning might be related to this information. Students appeared to successfully understand the intention of this photograph, enabling them to ignore other irrelevant items, such as the leaves and rocks at the riverbank. Students were then waiting for the next PowerPoint slide.

To assist students' understanding and generate more ideas about the content of this topic, Mr. Kimbley did not move directly on to the next slide but further explored students' interests about the photograph before the formal teaching session. He followed up by asking, "Anything you can find in the water?… Is that water warm or cold?". "Cold water" stated a student promptly identifying the temperature based on common sense. Indeed, the water temperature is one of the important variables affecting an organism's life habits in the water environment. One of the aims of this lesson was to build students' familiarity with the effects of temperature variations on the respiration rate of animals living in water. Students' answers showed that they deliberately or unwittingly predicted what they might need to know about in the day's lesson.

In this example, although the formal teaching of the biological content did not reside in the photograph, presenting an iconic diagram in advance was far from a redundant process because it could remind students of things to consider later in the lesson. Mr. Kimbley often used iconic diagrams in the form of photos to bring students' attention onto the concept they were going to learn, to help students organize their preexisting knowledge, and also to motivate them to continue their learning with their own questions. To begin a lesson with an advance organizer seemed to be a common approach for most teachers observed and is consistent with educational research findings. This short episode with Fig. 5.1 showed that an iconic diagram could serve the following three functions: to make teaching attractive for teenage students and to arouse their learning interest, to direct students' attention to the serious learning sessions to follow, and to pre-establish some prior knowledge for further teaching and learning.

5.3.1.2 Population Variations

In the following example, Mr. Dandridge started his lesson by introducing an iconic diagram followed by a line chart and demonstrated some unscientific notions by telling a 'story' about lemmings (shown in Fig. 5.2a) to attract students' attention on the main biological content of the lesson, namely *Population Variations*. Considering some students might not be familiar with this species and could have difficulty in understanding the story, Mr. Dandridge drew a line chart (Fig. 5.2b) highlighting the general population fluctuations of this species and helped lead the instruction to the

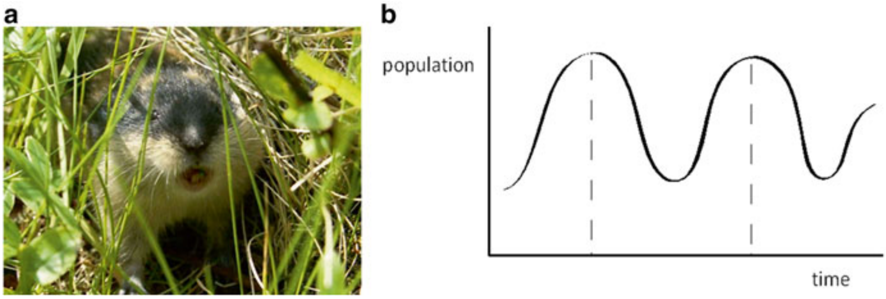

Fig. 5.2 (**a**) A photo of a lemming shown on the teacher's slide (This photo was taken by Frode Inge Helland and posted on Wikipedia Commons with GNU Free Documentation License) (**b**) A line graph of the population change of lemming (This graph was drawn on board by the teacher and recreated by the authors)

lesson's focus. The simple hand-drawn line chart was presented to students soon after the introduction of the photograph to supplement the previous usage of the iconic diagram and contribute to a better explanation of the population fluctuations. Subsequent to a background story about lemmings illustrated by this iconic diagram, the teacher moved the focal point of his teaching onto animal behavior and the change of a population cycle.

Mr. Dandridge: As you can see, this is a mammal. And there is a rumor: they jump off cliffs and commit suicide… that's nonsense. I mean, there is a computer game on this too. Its name is ….

Student: Lemming. (Only one student knew this animal and could answer the question, while others were reluctant to respond.)

Mr. Dandridge: Lemmings reproduce themselves so quickly but their population fluctuates dramatically, rather than following linear growth or regular oscillations. Lemming populations fluctuate before plummeting to near extinction. They just erupt and end up in the place where they can be found. And they come to a cliff and then it is the ocean. They jump off the cliff. So, what does it mean?

Students: A large number has died.

Mr. Dandridge: Its population changes along with its habitat environment, weather, food, shelter, predators…That's Darwinism. He therefore included or asserted that individuals must vary in their numbers according to the environmental conditions. Does this mean that all species perfectly fit the environment?

Students: No? I don't know why, I don't know.

Students: I guess some animals are well adapted to the environment.

Mr. Dandridge: Yeah, I suppose that's right. The species cannot be perfectly adapted, because the environment is always subject to change. There may be in the short term, and some in the long term. If you understand this, does anything else fill in the gaps? Most of the individuals are of high variation. What are the sources of variation? There are four types of possibilities: mutations, independent assortment, crossing over, random fertilization.

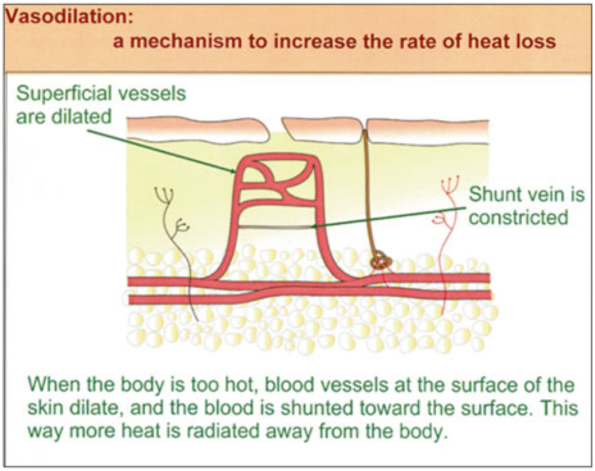

Fig. 5.3 An iconic diagram for vasodilation and a text illustrating the diagram, shown on the teacher's slide (This image was downloaded from SMART Exchange™, and reprinted with the permission from SMART Technologies)

In the instance above, recognizing the lemming and learning about their behavior was not the main content of this biology lesson. Presenting the photograph of a lemming gave students an example of a natural phenomenon that was relevant to how natural selection actually happens for a species. Furthermore, the line chart explained the information further and helped students better understand why the iconic diagram was presented. Therefore, the students obtained a sound advance organizer about the content and concepts that they were about to cover in the subsequent lessons.

Having students concentrate is not the ultimate goal for introducing iconic diagrams, for once the intention of the drawing has been perceived, students are able to organize their prior knowledge to readily and actively bring their imaginations into full play for the subsequent learning. The iconic diagram of the lemming functioned as a good example when introducing the concept – the *Population Variation*. Lemmings and the mysterious ideas associated with this animal's behavior gradually led the teacher's instruction into the main theory of the lesson about population variation.

5.3.1.3 Vasodilatation

Iconic diagrams were also used by teachers to provide explanations for conceptual learning. When a single static diagram has difficulty conveying a complex meaning, especially a holistic process that may have many factors involved, an appropriate combination of representations can help achieve a better learning outcome. Mr. Kimbley's PowerPoint slide on the topic 'Vasodilation' is shown in Fig. 5.3. When the teacher introduced the topic to explain the heat loss, he asked students if they were able to find the corresponding movement of blood vessels according to the changing temperature of the body by merely reading the diagram.

Receiving several responses to the negative, he briefly explained the function of vasodilatation by pointing to the diagram as detailed below:

Mr. Kimbley: You can imagine the feeling when your body temperature increases. How can the body temperature increase? [Pause while he awaits students' response.]

Students: Playing basketball or football.

Mr. Kimbley: Yes, sport makes the blood become hotter, and the skin of our body needs to make the evaporation process go faster so as to let the heat go out of the body. In this case, should the superficial vessels go closer or stay away from the surface? [Points at the diagram and shows the direction of dilation of the vessels.] …. That is what happens when you are playing basketball, your face gets flushed and you sweat more.

It is increasingly recognized that learning with multiple representations is more effective than learning with a single representation because each mode of representation has its own advantage of presenting a certain type of information (Waldrip et al. 2010). In this case, static diagrams cannot present the dynamic process of vasodilatation. Hence, learners could misinterpret the process because they cannot identify the dilation of vessels from the diagram. In this case, a second and more familiar form of representation can support learners in constructing a deeper understanding of the first complicated representation. By reading the text underneath and switching between the diagram and the text, students may gain a more complete understanding of the mechanism of vasodilatation.

5.3.2 Assertion 2: Teachers Used Different Diagrams Interchangeably to Facilitate Students' Understanding of a Concept Across Different Levels of Representations

During 7 months of observations, it was evident that schematic diagrams are important in understanding certain biology concepts. Almost all biology teachers devoted a relatively long time in explaining the schematic diagrams in their lessons. Most schematic diagrams appeared to correlate directly with the iconic diagrams that had been presented to students initially. Many concepts in the secondary biology lessons were explained at the microscopic or submicroscopic level to describe what happens outside of our direct experience or observation. In order to help students fully understand the topic, the teachers felt that it was necessary to explore the students' understanding of biological phenomena and to constantly navigate between the macro, micro, and sub-micro levels of representation.

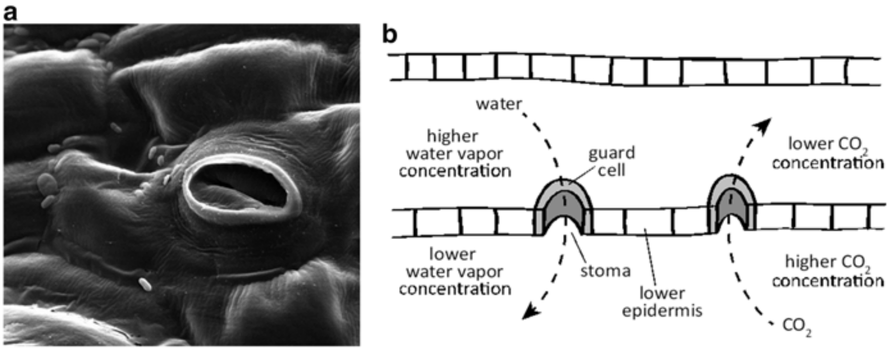

Fig. 5.4 (**a**) An image of a scanning electron micrograph (SEM) of a single stoma (This public domain image was taken from Wikipedia Commons) (**b**) A schematic diagram of the cross-section of the leaf to illustrate the structure and function of stomata (This diagram was drawn on board by the teacher and recreated by the authors)

5.3.2.1 Gas Exchange in Plants

Multiple representations can complement one another with regard to information and processes (Ainsworth 1999). More specifically, a second representation may be used to support learners as they interpret more complicated, abstract biological information (Tsui and Treagust 2003). The researchers observed a tendency for teachers to draw upon schematic diagrams to provide the detailed and in-depth explanation for the concept being studied in class. For example, Mr. Kimbley drew a simplified cross-sectional view of a plant leaf on the board to show the position and function of the stomata when the topic *Gas Exchange in Plants* was taught. The leaf epidermis is covered with tiny pores called stomata. Although the shape and appearance of stomata can be seen through a scanning electron micrograph (iconic diagram), the process of gas exchange between the air and the photosynthetic cells inside the leaf has to be explained by schematic diagrams (Fig. 5.4).

In particular, the schematic diagram was used to provide an explanation of the mechanism that cannot be illustrated by the iconic diagram alone. The iconic and schematic diagrams have their own unique attributes in demonstrating information from different representational levels. Students appeared to respond well to the sequence of learning a new concept by interpreting the iconic diagram first and then the schematic. They might have felt that the iconic diagrams are less intimidating and easy to interpret than the schematic ones. By being introduced to the iconic diagrams first, students were mentally prepared to make sense of the biological changes or processes that may be shown in corresponding schematic diagrams. Interpreting the schematic diagrams, in turn, seemed to help students understand the iconic diagrams better. (It should be noted that this simplified diagram may give a false

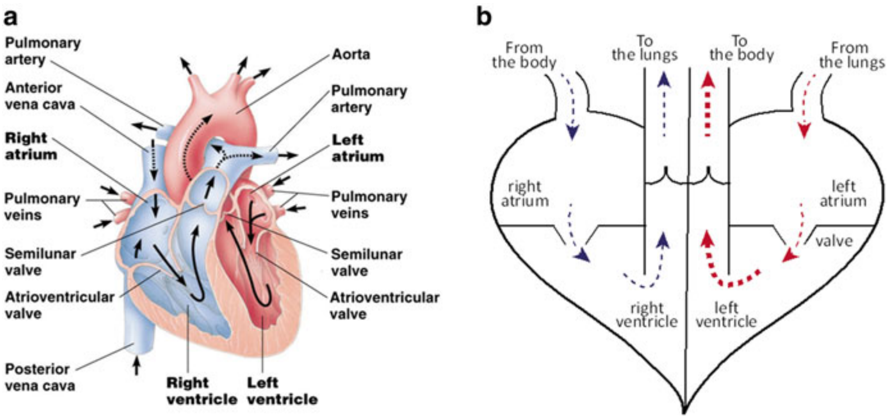

Fig. 5.5 (**a**) An iconic diagram for blood circulation in the heart (This diagram was originally published in *Campbell Biology* by Reece et al. (2011) and reproduced with the permission from Pearson Higher Education, Inc) (**b**) A simplified schematic diagram for blood circulation in the heart (This diagram was drawn on board by the teacher and recreated by the authors)

impression that the oxygen is not involved in gas exchange and some stomata allowed different gas exchanges (i.e., either water or carbon dioxide). However, this possible misinterpretation was not discussed in the lesson.)

5.3.2.2 Cardiac Cycle

One of the advantages of teaching with schematic diagrams lies in the property of eliminating those redundant details and thus making the essential information easier to understand. For example, it may be difficult to explain the circulation of blood in the heart with an iconic diagram (see Fig. 5.5a) because the iconic diagram is so 'real' that students need to have spatial skills and human anatomical knowledge to figure out how the different blood vessels and parts of the heart are connected and which way the blood flows. Mr. Barwick invented a simple schematic diagram in order to help students develop a better understanding of the iconic diagram and of the concept.

Mr. Barwick: Blood from the body systemic circuit enters the right atrium. Meanwhile, blood from the lungs enters the left atrium. [Pointing at the top right part on the iconic diagram] Ok? From the atria the blood flows into the corresponding ventricles. That means, from the right atrium to right ventricle; left atrium to left ventricle. [Referring to the direction of the blood moving from the top down] Happy enough?

Students: Yes.

Mr. Barwick: The two ventricles on the two sides of the heart then contract and expel blood into the arteries. [Pointing from bottom up] Right?

Students: Yes.

Mr. Barwick: To give you a clear picture of how the blood circulates between atria and ventricles, I am going to give you another chart. [Starting to draw a simple heart shape schematic diagram] I hope this one will be much easier for you to read. The blood leaves the left atrium to where?

Students: To the left ventricle.

Mr. Barwick: From right atrium to ….?

Students: To the right ventricle.

Mr. Barwick: Why is the left ventricle more muscular than the right ventricle?

Students: Because the left ventricle needs to contract harder and expel the blood into the whole body circulation.

Mr. Barwick: Good. What is the role of the valves?

Students: To prevent the blood from flowing in the opposite direction.

For explaining the blood circulation in the heart, Mr. Barwick introduced the iconic diagram that is full of colors and details (Fig. 5.5a) and the schematic diagram that bears a much simplified structure (Fig. 5.5b). As students' understandings developed, the teacher kept asking questions trying to ascertain students' learning from both images. In this instance, the schematic diagram presents the essential content knowledge but the information has been displayed in a different pattern. The schematic diagram eliminates the redundant visual details that may distract students' interpretations to reach the core information, namely the directions of blood circulation, the positioning of the ventricles and atriums, and the function of the valves. While students may retrieve some preliminary understandings from the iconic diagram, explaining with the schematic diagram provided the teacher with an additional pedagogical approach in complementing the use of the iconic diagram. Students were given an opportunity to achieve a better understanding of the concept by relating both diagrams.

5.3.2.3 Nervous System

The iconic diagram (Fig. 5.6a) shows the physical appearance of the neuron, whereas the schematic diagram of the Schwann cells (Fig. 5.6b) manifests both the structure of the Myelin sheath and saltatory conduction of a neural signal. Mr. Kimbley briefly explained the workings of the myelin sheath:

Mr. Kimbley: A common characteristic of all living organisms is they can detect changes in their environment and respond to them. To detect a change or stimuli, some form of communication between different parts of an animal's organism is involved. There are two coordinating mechanisms in animals that control their responses to stimuli: hormones and the nervous system. The nervous system is composed of cells called neurons, which specialize in carrying information. The shape of a neuron is shown in the above diagram. It possesses dendrites, an axon, and axon terminal at the end.

Mr. Kimbley slowly moved the focus from the iconic diagram (Fig. 5.6a) to the schematic diagram (Fig. 5.6b).

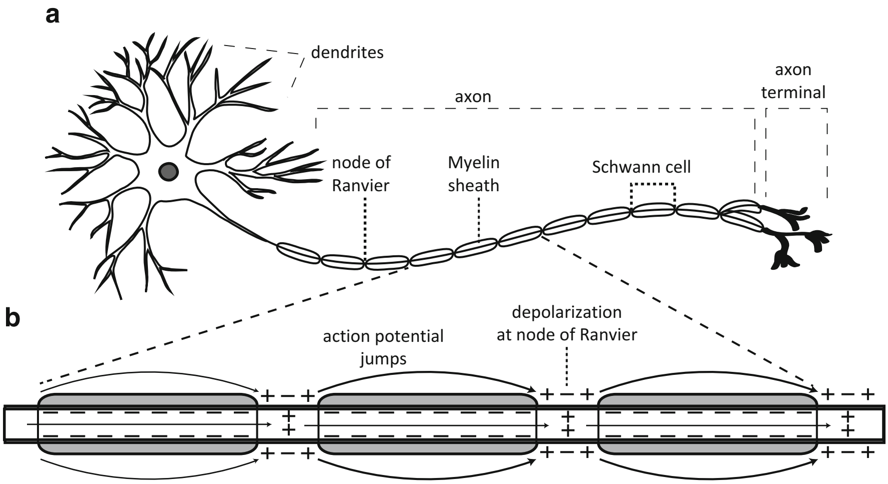

Fig. 5.6 (**a**) An iconic diagram of a neuron. (**b**) A zoomed-in schematic diagram of the cross-section of an axon to illustrate the saltatory conduction of an action potential (These diagrams were shown on the teacher's PowerPoint slide, and recreated by the authors)

Mr. Kimbley: The axon of a neuron is usually covered around with a layer, called a myelin sheath. The myelin sheath is essential for the neuron to transmit nervous signals properly. In the meantime, it provides protection for the axon being covered inside; it insulates the nervous impulse transmitted from other interference, thus to guarantee the accuracy and efficacy of signal transmission; and it helps increase the speed of the signal transmission through skipping every single Schwann cell, but by jumping from one node of Ranvier to the next node without increasing the diameter of the axon. [A metaphor has been introduced here to help explain the meaning of skipping.] Impulse jumps like a kangaroo and moves quickly from one node to another. And that makes the velocity of saltatory conduction higher than smooth conduction.

In the case above, the teacher explained the biological content with two diagrams, one after another. In the very beginning, he referred to the iconic diagram on the top to show students the physical shape of the entity – *a neuron*. The teacher also introduced some terminologies, such as *dendrites*, *axon, myelin sheath*, and *Schwann cell* because students needed to recognize the specific parts of the image according to the terms. Mr. Kimbley's instruction continued with the schematic diagram by depicting the functions of those parts within the nervous system. A schematic diagram was employed to describe the transmission of the nervous signal that is at the sub-micro level and cannot be directly observed. This sub-micro level diagram illustrates a phenomenon on a different scale and hence is more abstract to comprehend (Davidowitz and Chittleborough 2009). Compared to iconic diagrams that have an advantage of showing matters at the macro or micro level, such as representing the tangible biological substances or visible phenomena, schematic diagrams can have the attributes to provide students with some insight into the underlying mechanism and principles embedded in the phenomena. In this lesson, when Mr. Kimbley shifted his explanation of the content through the iconic to the schematic diagram, students needed to develop their own conceptual interpretation by relating both diagrams. The teacher spent more time and effort in explaining the schematic diagram than the iconic diagram for during his instruction.

5.3.2.4 Human Respiratory System

In a similar manner, for the *Human Respiratory System*, Mr. Kimbley emphasized an understanding of the schematic diagram in relation to the corresponding iconic diagrams. However, for this lesson, he paid particular attention to the different scopes of the diagrams (that is, macroscopic, microscopic, and submicroscopic diagrams). Research studies have found that a better conceptual learning occurs when students can effectively move back and forth between the different levels of the diagrammatic representations (Chittleborough and Treagust 2007), but the connections between macro, micro, and submicroscopic representations are not always apparent and explicit to students (Davidowitz and Chittleborough 2009). Many biology teachers, including Mr. Kimbley, are aware that the submicroscopic process of the gas exchange in the lungs may be difficult for students to understand, and when links are not made explicit between different levels of representation, students may misinterpret the diagrams and misunderstand the concept. To support students to construct a better conceptual understanding and to move freely from observing the macroscopic level of the phenomenon to the submicroscopic level of thinking, the teachers paid considerable attention explicitly showing the connection and explaining the diagrams and the biological processes.

Figure 5.7 is a set of diagrams Mr. Kimbley used to explain the gas exchange in the human respiratory system. These three diagrams are sequentially zoomed-in from a macroscopic to a microscopic and once again to a submicroscopic level. Instead of assuming that students will recognize the schematic diagram, the teacher led the students to a better understanding of gas exchange in the alveolus by gradually moving from one diagram to the next, and then explaining the submicroscopic mechanism of blood circulation and gas exchange in detail. Here is how the teacher started explaining the gas exchange in the alveoli:

Mr. Kimbley: (with Fig. 5.7a) Let's follow a breath of air from start to finish. [Pointing at the nose on the diagram] The air goes into the nose or mouth and goes into the trachea or windpipe. The end of your trachea splits into an upside down Y-shape and forms the bronchi. Air passes through the windpipe and reaches both sides of the lungs. And the lungs are protected by the ribcage.

Mr. Kimbley finished the explanation of the physical features of Fig. 5.7a and then moved to the next diagram.

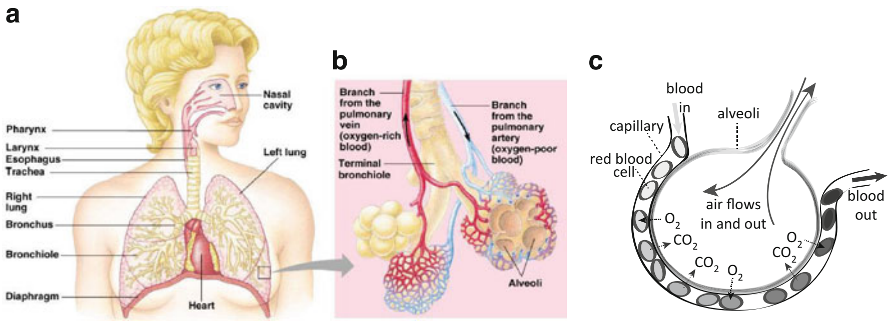

Fig. 5.7 (**a**) An iconic diagram of a human respiratory system. (**b**) A zoomed-in image of the lung to show the bronchioles and the alveoli (These two diagrams were originally published in *Campbell Biology* by Reece et al. (2011), and reprinted with the permission of Pearson Higher Education, Inc). (**c**) Another zoomed-in cross-sectional diagram of the alveolus and the capillary to illustrate the gas exchange between alveolar air and blood (The original diagram was presented on the teacher's PowerPoint slide, and the image was recreated by the authors for clear communication)

Mr. Kimbley: (with Fig. 5.7b) Inside of the lungs, the bronchi branch off into lobes, which look similar to branches of a tree. The air flows through the bronchioles until the air reaches the ends of the branches, which are clusters of little pockets that have the form of hollow cavity, called alveoli. Alveoli are the final branches of the respiratory tree and act as the primary gas exchange units of the lung. The blood brings carbon dioxide from the body and releases it into the alveoli, and oxygen in the alveoli will be taken up and transported to the cells all over the body.

The teacher explained the direction of blood flow in Fig. 5.7b and then started to explain the gas exchange mechanism with Fig. 5.7c.

Mr. Kimbley: (with Fig. 5.7c) When the air reaches the alveoli, oxygen diffuses through the membrane into small blood vessels called capillaries, and carbon dioxide diffuses from the blood in the capillaries into the alveoli.

Once Mr. Kimbley finished the explanation of the macroscopic iconic diagram (Fig. 5.7a) for the physical characters of the lungs, he turned to the other diagrams (Fig. 5.7b, c) to direct students' attention to the microscopic features (the direction of the blood circulation around the alveoli), and to the submicroscopic features (the mechanism of the gas exchange in the alveoli). In other words, the connections between the macroscopic and molecular levels were intentionally highlighted to help students understand the whole process of gas exchange at multiple levels of representation: how air comes through to the alveoli (macroscopic), how oxygen and carbon dioxide are exchanged (submicroscopic), and then how the air gets out of our body (macroscopic). This zooming-in and zooming-out of the human body using multiple diagrams seemed to provide a good opportunity for students to construct scientific mental models that interconnected the different scopes of the concept. Another important reason why Mr. Kimbley switched between different diagrams was to curb the difficulty of interpreting and visualizing the submicroscopic schematic features of the biology concept. The teacher tried to activate the students' prior knowledge through the iconic diagrams, and used it to help students interpret the schematic diagram and finally integrate them together to form a better understanding of the gas exchange. When the observed biology teachers introduced multiple diagrams jointly for a concept, they mixed the scopes (macroscopic, microscopic, and submicroscopic) and the types (iconic and schematic) of diagrams to guide students' learning.

5.3.3 Assertion 3: Teachers Frequently Adopted Analogical Explanation While Teaching with Diagrams

The main goal of this study was to examine different types of diagrams used in teaching biology. The researchers noted that teachers often adopted analogies along with diagrams, especially when students appeared to have difficulty in understanding complicated diagrams or new biological concepts. Analogy's potential as a powerful tool for teaching lies in making the instruction of new material intelligible to students by comparing the analog to something they are already familiar with (Orgill and Bodner 2005). For example, when Mr. Kimbley introduced the structural functions of neurons, he drew an analogy in terms of similar appearance between axon and electric cable, and later between a Schwann cell and a German sausage:

Mr. Kimbley: (pointing at the diagram) You can imagine this is a cable wire (students laughed). Sensory neurons are activated by the stimuli such as light, sound and temperature (tapping one end of the cable in his hand). It is a one-way, single direction transmission. The signal goes from the outside environment to the internal central nervous system. The axon is covered by layers of myelin sheath. Let's say the metal part of the cable is covered by the rubbery skin.

In this class, the researcher observed that the lesson was becoming abstract and noticed that students were very quiet. When Mr. Kimbley introduced this analogy, however, it broke the classroom dynamic and made the students burst into laughter. From a quick glance, students might have thought that a neuron from the diagram does not look anything like an electric cable that they know, especially with all the dendrites and axon terminals at either ends. However, Mr. Kimbley was referring to the axon and the myelin sheath, rather than a neuron, when he introduced the analogy of a cable. Axon is coated by myelin sheath, as copper wire is covered by plastic. The neural signal is transmitted from one end to the other, as electric wire carries electric current. Based on the similarity in the appearance, the teacher introduced this analog to draw parallels in the structure and functions of an axon with an electric wire. As a complement to the diagrams of a neuron (see Fig. 5.6), the analogy seemed to help students interpret the diagram better by connecting the new concept to something they already knew.

In another class, Mr. Dandridge used an analogy to explain the kidney's excretion process. Rather than drawing on the similarity of appearance, he drew an analogy based on the similarity in the process. After explaining the glomerular filtration and the tubular reabsorption with an elaborate diagram drawn on board, he summed up the overall process with a pencil case, which he picked up from a student's desk. Unlike the above example of the electric cable analogy for the neuron, the kidney (or any part of the kidney) does not remotely resemble a pencil case. However, he focused on the similarity in the process of sorting out pens from a pencil case with the process of the filtration and reabsorption in the kidney. He explained that there are two common strategies to sort out pens from a pencil case: one strategy is looking into the pencil case and taking out the ones that you would not need; the other is dumping the whole content on the table and then putting the ones that you would need back into the pencil case. The second strategy is not necessarily more efficient than the first one, but Mr. Dandridge noted it is similar to the excretion process in the kidney. Because this pencil case analogy is not directly drawn from the similarity in appearance, it did not seem to play a complementary role in helping students interpret the diagram itself. However, Mr. Dandridge adopted this analogy in order to help students to move between different scopes or representations of the concept – the detailed visual understanding of the excretion process through the diagram versus the holistic understanding of the process through the analogy.

In the learning process, the strength of analogies lies in their abilities to provide additional visualization of abstract concepts and to compare similarities between students' prior knowledge and the target concepts. In the classroom observations, the researchers noted that the participating teachers tended to adopt analogical explanations while including diagrams, especially when they were having difficulty explaining some aspect of a diagram or the biology concept. Often, this was a prompt for providing an analogical explanation. Some examples are shown in Table 5.1. The combination of diagrams and analogies were found to have the potential of facilitating students' development of in-depth understanding of the topic. When students were having difficulty interpreting diagrams, the teachers used analogies with similar looks to help reduce the difficulty. When students needed to build understanding of biological functions and procedures in a broader perspective, the teachers used analogies along with diagrams to help students integrate different scopes and representations of the concepts.

The teachers tended to draw upon analogies that either come from the learners' knowledge base or experience of daily life (Treagust, Harrison, and Venville 1998). The sources of analog were quite varied. Mr. Kimbley and Mr. Dandridge had developed a considerable repertoire of analogies over several decades of teaching, many of which they had developed from the extensive professional reading. While Mr. Dandridge relied more on biology curriculum packages and teachers' handbooks as the main sources of analogy, Mr. Kimbley used various sources, and sometimes adopted multiple analogies to help explain a single biology concept shown by a diagram. As experienced biology teachers, they both were able to improvise many analogies as well. In general, almost every observed biology teacher taught with self-designed diagrams with analogical features (see Table 5.2).

Table 5.1 Selected analogies used by the biology teachers during the lessons observed

Topic	Teachers	Grade	Analog	Target concept	Similarities
Nervous system	Mr. Kimbley	12	Cable wire	Neuron	Structural: Axon is covered by layers of myelin sheath Functional: The neural signal is transmitted from one end to the other
Cell metabolism	Mr. Dandrige	11	Lock and key	Enzyme and substrate	Structural: Interlocking grooves Functional: One type of enzyme corresponds to only one kind of molecule
Respiratory system	Mr. Kimbley	12	Mexican walking fish	Bronchioles	Structural: Tiny little branches coming off from the center
Excretory system	Mr. Dandrige	12	Sorting out pens from a pencil case	Kidney filtration and reabsorption	Functional: Dumps everything in the beginning and gathers back the ones that are needed

Table 5.2 Sources of diagrams and extended analogical explanations

Teacher	Target students	Teacher's handbook	Online resources	Improvisational
Mr. Kimbely	Year 9, 11, 12	✓	✓	✓
Mr. Dandridge	Year 11, 12	✓		✓
Mr. Barwick	Year 9, 10	✓		
Mr. Cobbs	Year 9, 10	✓	✓	
Mr. Stradford	Year 9	✓		

These analogies were generally closer to students' experiences and functional in nature. They were different to conventional models where structural attributes are simply exaggerated (Gilbert 2008). The concrete analogs presented by the teachers were related to daily life and thereby facilitated students' learning by providing visualization of abstract concepts. Students also showed interest when they could find some non-biological entities that had similar properties with the concept they just learned. The frequent uses of analogical visuals appeared to make learning biology much easier and enjoyable for these teenage students.

Evidence from these observations confirms previous findings that analogies allow teachers to consider students' prior knowledge and therefore help facilitate understanding of the abstract content by pointing to similarities that incite learning interests and have a motivational function in representational learning (Ainsworth 2008).

In our observations of these biology teachers, the function of analogies was used to facilitate visualization of abstract concepts that are embedded within diagrams with which students had difficulty making sense. Analogical explanations may be necessary for students to understand both diagram and the concept.

5.4 Limitations

One hundred and twenty biology lessons taught by five teachers in one high school who were willing to participate in the research formed the basis of this research. The five biology teachers were experienced and actively used visuals as part of their teaching in which they tended to adopt didactic teaching approaches. This study did not examine how diagrams were used in practical lessons in the laboratory due to limited opportunity and time constraints. The prevalence of didactic teaching approaches may be influenced by the instructional facilities and equipment available, the school culture and tradition, and the students' habits of learning. Future research needs to investigate how diagram are used by teachers whose teaching tends to be less didactic and more student-centered. Thus, it is acknowledged that the small sample of participant teachers are not representative of all biology teachers, and other teachers' use of diagrams in biology teaching may have different orientations to the teachers observed in this study.

5.5 Conclusions

This interpretive study into biology teachers' use of diagrams generated three assertions drawn from the observations into the different ways that diagrammatic representations can be used to explain biological concepts. As noted previously by Cheng and Gilbert (2009), the findings of the study indicate that diagrams are a valuable tool in demonstrating scientific concepts and that they are handled by teachers with much flexibility. The assertions in this study showed that different diagrams were employed for different instructional purposes – introducing the topic, explaining the content knowledge across different representational levels, evaluating students' learning, and integrating with analogical features. The assertions should be seen as an evidence of the everyday instructional practice of teaching secondary biology with diagrams.

References

Ainsworth, S. (1999). The functions of multiple representations. *Computers & Education, 33*, 131–152.

Ainsworth, S. (2008). The educational value of multiple-representations when learning complex scientific concepts. In J. K. Gilbert, M. Reiner, & M. Nakhlel (Eds.), *Visualization: Theory and practice in science education* (pp. 191–208). Springer.

Cheng, M., & Gilbert, J. K. (2009). Towards a better utilization of diagrams in research into the use of representative levels in chemical education. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education* (pp. 55–73). Springer.

Chittleborough, G., & Treagust, D. (2007). The modelling ability of non-major chemistry students and their understanding of the sub-microscopic level. *Chemistry Education Research and Practice, 8*(3), 274–292.

Cook, M., Wiebe, E. N., & Carter, G. (2008). The influence of prior knowledge on viewing and interpreting graphics with macroscopic and molecular representations. *Science Education, 92*(5), 848–867.

Davidowitz, B., & Chittleborough, G. (2009). Linking the macroscopic and sub-microscopic levels: Diagrams. In J. K. Gilbert & D. Treagust (Eds.), *Multiple representations in chemical education* (pp. 169–191). Springer.

Erickson, F. (1986). Qualitative methods in research on teaching. In M. Wittrock (Ed.), *Handbook of research on teaching* (pp. 119–161). New York: Macmillan.

Erickson, F. (2012). Qualitative research methods for science education. In B. J. Fraser, K. G. Tobin, & C. J. McRobbie (Eds.), *Second international handbook of science education* (Vol. 2, pp. 1451–1469). Dordrecht: Springer.

Gilbert, J. K. (2008). Visualization: An emergent field of practice and enquiry in science education. In J. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 3–24). Springer.

Hegarty, M., Carpenter, P. A., & Just, M. A. (1991). Diagrams in the comprehension of scientific texts. In R. Barr, M. L. Kamil, P. Mosenthal, & P. D. Pearson (Eds.), *Handbook of reading research* (Vol. 2, pp. 641–668). New York: Longman.

Kozma, R. (2003). The material features of multiple representations and their cognitive and social affordances for science understanding. *Learning and Instruction, 13*(2), 205–226.

Lynch, M. (1990). The externalized retina: Selection and mathematization in the visual documentation of objects in the life sciences. In M. Lynch & S. Woolgar (Eds.), *Representation in scientific practice* (pp. 153–186). Cambridge, MA: MIT Press.

Mayer, R. E., & Moreno, R. (2003). Nine ways to reduce cognitive load in multimedia learning. *Educational Psychologist, 38*(1), 43–52.

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

Novick, L. R. (2006). The importance of both diagrammatic conventions and domain-specific knowledge for diagram literacy in science: The hierarchy as an illustrative case. In D. Barker-Plummer, R. Cox, & N. Swoboda (Eds.), *Diagrams 2006, LNAI 4045* (pp. 1–11). Berlin: Springer.

Orgill, M. K., & Bodner, G. (2005). The role of analogies in chemistry teaching. In *Chemists' guide to effective teaching* (pp. 90–105). Upper Saddle River, NJ.

Pozzer, L. L., & Roth, W.-M. (2003). Prevalence, function, and structure of photographs in high school biology textbooks. *Journal of Research in Science Teaching, 40*(10), 1089–1114.

Reece, J. B., Urry, L. A., Cain, M. L., Wasserman, S. A., Minorsky, P. V., & Jackson, R. B. (2011). *Campbell biology* (9th ed.). San Francisco: Pearson.

Roth, W.-M., Bowen, M. G., & McGinn, M. K. (1999). Differences in graph-related practices between high school biology textbooks and scientific ecology journals. *Journal of Research in Science Teaching, 36*(9), 977–1019.

Treagust, D. F., Harrison, A. G., & Venville, G. J. (1998). Teaching science effectively with analogies: An approach for preservice and inservice teacher education. *Journal of Science Teacher Education, 9*(2), 85–101.

Tsui, C.-Y., & Treagust, D. F. (2003). Genetics reasoning with multiple external representations. *Research in Science Education, 33*(1), 111–135.

Waldrip, B., Prain, V., & Carolan, J. (2010). Using multi-modal representations to improve learning in junior secondary science. *Research in Science Education, 40*(1), 65–80.

Chapter 6
Teaching Stoichiometry with Particulate Diagrams – Linking Macro Phenomena and Chemical Equations

Maurice Man Wai Cheng and John K. Gilbert

Abstract This chapter explores a way stoichiometry is introduced to secondary school students that aims at fostering a conceptual understanding and a relational understanding of the chemistry triplet (i.e. macro, submicro and symbolic). We start by discussing students' difficulties in understanding macro phenomena, submicro and symbolic representations that are relevant to the learning of stoichiometry. Then we argue that a teaching sequence starting with macro phenomena, then a submicro representation of the corresponding macro phenomena, and finally deriving a chemical equation based on the submicro representation, should be likely to facilitate students' understanding of stoichiometry. Strategies that guide the selection of a particular macro phenomenon and diagrammatic representation of submicro interactions are proposed. We then analyze a lesson that was conducted based on the design. Particularly, we focus on good practice of teaching with diagrammatic representation of submicro phenomena that served to link macro phenomena and chemical equations as symbolic representations.

Keywords Stoichiometry • Equations • Chemistry • Macro and micro phenomena • School science culture • Symbolic representations • Teaching sequence • Graphic organizer • Mental representation • Diagram

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6.1 Introduction

This chapter is based on the premises that chemistry learning can be a very challenging task to many students. A part of the reason is that a chemical idea is often represented in different ways. We will discuss some difficulties students may face when they learn stoichiometry in the light of their possible experiences in doing practical activities (the combustion of magnesium, for example), and in understanding submicro and symbolic representation of the concept.

6.1.1 Learning of Macro Phenomena

In chemistry, a vast variety of substances are reduced to 'simple' and pure forms so that models of properties of substances, such as solubility, hardness, chemical reactivity, the amount of which that would react with another substance, can be developed. Pedagogically, instead of investigating metal objects in the form of window frames, water pipes or the body of mobile phones, very often strips of pure metals are studied. We teachers may use 'oxygen' to replace 'air' or use them interchangeably (irrespective of the possible students' prior learning that oxygen constitutes only around 21 % of air!) when we talk about a practical activity that involves oxygen, for example, the combustion of metals. While teachers can easily move from the daily phenomena to the macro phenomena – metal objects of different specific functions represented as decontextualized metal strips; air represented as oxygen – they may not be aware that such a 'simplification' can be a hurdle to many students. Having to reason with macro phenomena can be regarded as a 'border crossing' activity in which students would have to cross from their daily culture to the school science culture (Aikenhead 1996).

Students also have to handle the procedural and conceptual aspects of practical activities, understand the conceptual underpinnings of procedures, and to arrive at certain conceptual understanding from the results, after completing the procedures. Yet much of the lesson time seems to have spent on the procedural aspect of practical activity (Abrahams 2011) and that there are so much procedural 'noise' in practical activities (Hodson 1993). Moreover, students have to deal with 'inconsistent results, inconclusive results, and even no results'. There should be little surprise that students find learning macro phenomena in chemistry a formidable task. Watson et al. (1995) investigated the effect of practical work on students' understanding of combustion. In one of their assessment items, students were asked to choose among five possible reasons why burning of 6 g magnesium could yield a product of 10 g. It was found that among 149 English students aged 14–15 who had extensive practical experience of burning of metals, only 26 % picked the scientific explanation (21 % chose the option 'the result was impossible'; 27 % did not respond). Take another item that assessed the idea of mass conservation – as a basis for the learning of stoichiometry – as an example, only 30 % of Hong Kong Year 8 students (aged 13–14) believed that the total mass of 10 g salt and 100 g water conserved after the salt is dissolved in water (Cheng 2013). Although the question demanded macro understanding only, it could still be a challenge.

6.1.2 Learning of Submicro Representations

Chemistry can be characterized as making sense of macro phenomena through the interactions of submicro entities. In this connection, there are three issues that may impede students learning:

(1) Research studies over the years have reported that some students may ascribe macro properties of substances to the properties of individual submicro entities. For example, some students explained the thermal and electrical conductivity, malleability and the strength of metals in terms of individual atoms having these properties (Ben-Zvi et al. 1986). Combustion of a substance was regarded as the burning of atoms, and hence these atoms vanish (Andersson 1990). Rusting was regarded as the rusting of iron atoms. Students' commitment to perceptual-based explanations of physical phenomenon can impede their learning of chemistry in terms of submicro entities (Jaber and BouJaoude 2012).

(2) Some representations used in classroom teaching (in textbooks and in science curricula) may impede meaningful learning (Taber 2002). For example, ionic compounds such as sodium chloride are often represented and emphasized as an ion pair formed by the electron transfer from a sodium atom to a chlorine atom. Such a representation is believed to be closely related to students' representations of an ion pair of sodium and chlorine atom (e.g., in Ben-Zvi et al. 1987) and hence their difficulties in explaining macro properties of substances (Taber 2001). Also, it has been shown that teachers' talk may rapidly jump between macro phenomena and submicro entities, and use words and symbols unspecifically (e.g., the use of "water" and "H_2O" to refer to liquid water and water molecules at different occasions). Such a practice have made the successful learning of science unlikely to happen (Stieff et al. 2013).

(3) The learning of submicro entities is complicated by the variety of representation modes. Inherently each of these modes has its limitations. For example, a weak acid is usually represented in diagrams by a few circle pairs (usually labeled as 'HA') and two (or four) solitary circles (labeled as H^+ and A^-). While it represents the idea of partial dissociation of a week acid, it significantly amplifies the percentage of week acid molecules that dissociates in water. It is through the degree of dissociation (a mathematical mode) that the percentage of dissociated molecules is represented (Cheng and Gilbert 2009). Students would have to select and integrate ideas represented in the diagrammatic and mathematic modes. It is likely that some students may not be able to select and construct meanings in the scientific sense. In a similar way, diagrammatic

mode may not represent the relative size of an atom, electron shells and atomic nucleus accurately. Other modes of representation, such as an analogy, have to be used to represent the massive size of an atom as compared with that of its nucleus (Harrison and Treagust 1996). The demands for selecting and integrating information from different modes of submicro representations could create a hurdle to students' learning.

6.1.3 Learning of Symbolic Representations

Learning to manipulate symbols that represent macro phenomena, submicro entities and their interactions is an extremely demanding task (Taber 2009). There might have been an unexamined assumption that learning of science would be deemed successful if students were able to just handle this most abstract representation. However, it has been shown that those who were able to balance the chemical equation $3H_2 + N_2 \rightarrow 2NH_3$ would represent the product as a row of six connected hydrogen atoms (Yarroch 1985); and students are more likely to solve a simple task in stoichiometry that demanded algorithmic mathematical manipulation than a similar task that assessed conceptual understanding (Nurrenbern and Pickering 1987). Also, although there was a significant difference between higher and lower ability students in solving algorithmic problems on stoichiometry, these groups demonstrated no difference in their performance in solving conceptual tasks (Cracolice et al. 2008). In short, being able to balance chemical equations or to solve quantitative problems in stoichiometry does not guarantee a conceptual understanding or an understanding of the meanings behind these symbolic manipulations.

The learning of stoichiometry in school chemistry demands a prior understanding of concepts related to that of the mole. Other than having to understand chemical formulae, the meaning of 'stoichiometric coefficient' and the notation of chemical equations (e.g., Sanger 2005), the learning of stoichiometry is complicated by need to manipulate the wide range of numerical figures that are often represented by scientific notations. Such a difficulty was reported in Gabel and Sherwood (1984). Students ($n = 332$, high school level) were asked to calculate the number of oranges/granules of sugar, their weight or their volume based on some given data. The tasks were analogical to those demanded in calculation based on the mole concept, for example, to find out the mass, volume or number of particles based on given information. It was found that there were statistically significant differences between students' performance when they handled granules of sugar that demanded manipulations of (i) the number of concrete item 'bag' and the word 'billion', and (ii) huge numerical figure represented as 'billion' and using scientific notation. Also, it was found that students performed significantly better when the numbers they manipulated involved a whole unit rather than a fractional unit (e.g., if a dozen oranges weighted 4 lbs, how many oranges would you have if you had 20 lbs of oranges *vs.* if you had 3 lbs of oranges?). In short, students face two aspects of challenges in their learning of symbolic representations of stoichiometry: (i) to make sense of various notations and their conceptual meaning used in chemical equations; (ii) to handle the mathematics that represents the amount of reactants and products.

Given the myriad number of possible challenges students might face in their learning of stoichiometry, careful decisions must be taken on how various representations are orchestrated in classroom teaching in order to facilitate meaningful learning. In the next section, we will propose a teaching sequence on the use of different representations in the teaching of introductory stoichiometry. A chemistry lesson will then be analyzed in the light of such a teaching sequence.

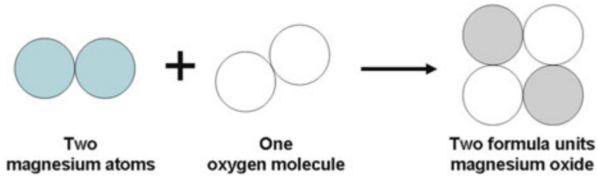
6.2 Towards a Teaching Sequence for Introductory Stoichiometry

There have been various suggestions on the teaching of concepts related to amount of substance and stoichiometry. These suggestions included: using the idea of 'amount of substance', 'chemical amount' and 'the mole' according to consensus in the scientific community (Nelson 2013); using a graphic organizer to tabulate the simplest stoichiometric ratio and hence the mass of each of the reactants and products (so as to highlight the concrete mass relationship) before embarking on solving a problem (Koch 1995); having students to visualize – through imagination – the gigantic magnitude of Avogadro's number (e.g., the volume of 6.02×10^{23} grains of sand (van Lubeck 1989), the volume of Pacific Ocean as 7×10^{23} ml (Alexander et al. 1984)). These strategies have their values in enhancing students' understanding. As the roles of the triplet (Gilbert and Treagust 2009; Talanquer 2011; Taber 2013), and their visual representations (Gilbert et al. 2008), have now been established, they should inform the development of teaching strategies that enhance students' conceptual understanding of stoichiometry.

The reaction between magnesium and oxygen, which may be regarded as an exemplar chemical reaction for the teaching of stoichiometry, can be represented as one or many of the following ways:

(1) The chemical equation with or without the physical states of the substances: $2\ Mg + O_2 \rightarrow 2MgO$ (symbolic).
(2) The concrete amount of magnesium metal and oxygen gas reacted and the amount of magnesium oxide produced, e.g. 24.3 g Mg, 16.0 g O_2, 40.3 g MgO/48.6 g Mg, 31.0 g O_2, 80.6 g MgO. (macro)
(3) Students may compare the mass of a piece of magnesium and the mass of its oxide after a complete combustion (macro). The recorded data would form the basis through which students would learn, explore, or verify stoichiometry.
(4) Students may conduct and observe the combustion of a piece of magnesium (macro). Also, they may be asked to predict and measure the relative mass of the magnesium and its oxide qualitatively.
(5) A 2D diagram showing the simplest ratio of the number of magnesium atoms, oxygen molecules and formula units of magnesium oxide involved in the

Fig. 6.1 A submicro representation of the combustion of magnesium



chemical reaction/equation (submicro) (see Fig. 6.1). In many textbooks, such a kind of diagram is placed under its corresponding chemical equation. It is likely that textbook authors intend to support students' understanding of the chemical equation.

(6) A 2D diagram showing a certain number of the chemical species involved in the chemical reaction/equation (submicro), e.g., a stack of 6×6 regularly and closely packed circles representing a part of magnesium solid and some circle pairs representing oxygen gas at one side, and a stack of 6×12 regular and closely packed circles at an other side representing a part of magnesium oxide as the product. Compared with Fig. 6.1, this diagram, to a certain extent, represents the physical state of the chemicals. Such a diagram intends to facilitate students' association of the combustion of magnesium (macro) with the interaction of chemical species at the submicro level. Nevertheless, the number of chemical species is not identical to the stoichiometric coefficient. It would be a challenge for students to associate the diagram with its chemical equation.

Given the variety of activities and representations that are available, how to select them and how they should be orchestrated in classroom teaching becomes an issue. Research studies have shown that students tended to adopt algorithmic manipulations and lacked conceptual understanding of stoichiometry represented in particulate diagrams (a form of diagram in which submicro entities are represented as circles or clusters of circles). There have been suggestions that teachers should use more proper definitions of scientific concepts and should help students to relate Avogadro's number/stoichiometry with macro phenomena. While we find these advices useful, we believe that unless students are taught to mentally visualize submicro phenomena/interactions, their conceptual understanding of stoichiometry cannot be guaranteed. In this connection, we would like to suggest that the teaching of introductory stoichiometry will possibly be most meaningful to students when the macro phenomena, submicro and symbolic representation are utilized. And it is important that teachers should avoid confusing students by jumping across different representations (Stieff et al. 2013) before students develop competence in each of the representations. In the following sections, we will propose,

(i) a general sequence of representations that teachers may adopt in order to facilitate students' construction of ideas of stoichiometry, and
(ii) specific representations, based on (1) to (6) discussed above, that teachers may use to facilitate learning of stoichiometry.

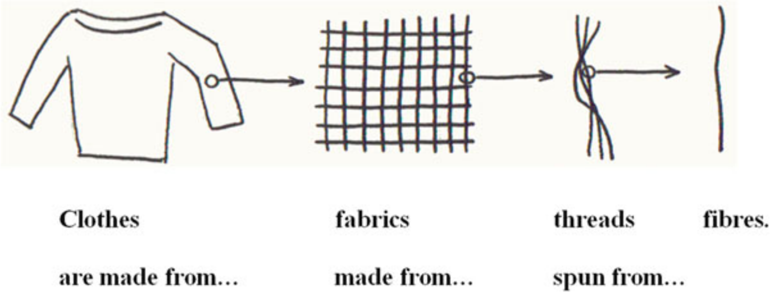


Fig. 6.2 An approach of exploring properties and structure (Redrawn based on Hill et al. 1989, p. 41)

6.2.1 A General Approach to a Teaching Sequence

We concur with Johnstone (1982, 2010) that macro, submicro and symbolic representations are equally important and that simply working with macro phenomena alone may constitute meaningful learning experience for students. We are also aware that teachers around the world are working with curricula that are decided by local or national authorities (Risch 2010). It is still a norm that competence in school chemistry is defined in terms of students' relational understanding of macro phenomena, submicro and symbolic representations.

It has been suggested that it is good practice to start teaching a new chemical idea with an investigation of the corresponding macro phenomena. Take the teaching of structure and properties of materials as an example, Millar (1990) recommended that students could start by exploring (1) the properties of a woolen jumper, and then (2) how pieces of fabric make up the jumper, (3) how threads make up the fabric, (4) how threads are spun from fibres (Fig. 6.2). This exploration exemplifies a sequence through which students would better handle the materials macroscopically (the woolen jumper) at the outset.

The sequence is coherent with the psychological principle of learning that students should explore phenomena that they are familiar with at the outset (Nelson 2002; Johnstone 2010). The properties of the phenomena under investigation are made sense of at another level that students can readily visualize. Such a sequence is useful for teachers when they plan their teaching of structure–property relationships in chemistry. We propose that the sequence can readily be extended in the teaching of stoichiometry.

Pedagogy that starts with exploring macro phenomena has also been investigated in the teaching and learning of chemical reactions, such as the combustion of reactive metals, metal ion displacement, the neutralization of acids and alkalis/metal oxides, ionic precipitation reactions (Treagust and Chandrasegarana 2009). This study suggested a teaching sequence that fosters Grade 9–10 students' understanding of the triplet relationship. In the control group, students were taught 'traditionally', meaning that teaching activities involved practical activities (macro) and writing balanced and ionic equations (symbolic). In the experimental group, students were taught submicro representations of the corresponding chemical reactions as well. Post-test comparison of the two groups showed that the learning of the experimental group was better than the control group.

The teaching sequence adopted in the experimental group was that students were taught submicro representations of the macro phenomena before they learnt to represent through chemical equations. Also, submicro representations were used as an explanation of the observed chemical changes. Ionic equations were hence deduced, rather than merely arrived at by crossing out the spectator ions from chemical equations (*ibid.* Figure 7.3, p. 159). Given the positive outcome of this teaching strategy, it is suggested the teaching sequence can be extended to the introduction of stoichiometry. A general teaching sequence of stoichiometry is hence proposed:

(1) A macro phenomenon/phenomena are introduced to students, possibly as a practical activity. As suggested by Hodson (1993) and Abrahams (2011), measures should be taken to ensure students are not distracted by the procedural understanding and handling apparatus. Also, observable results should be apparent to students.
(2) A submicro representation(s) of the macro phenomenon is then discussed with students. As suggested by Johnstone (2010) and Stieff and his colleagues (2013), it is important that teachers should avoid too rapidly jumping across different representations in their teaching. As submicro representations are often in the form of diagrams, measures should be taken to ensure students are able to decode and relate different components of the diagrams so that they can interpret the diagrams as intended by the teachers.
(3) A symbolic representation(s) is deduced from the submicro representation. As far as writing a chemical equation is concerned, students should be guided towards its relationship with the submicro representation and macro phenomena. The meaning of stoichiometric coefficient and subscript, where applicable, should be differentiated. It is through the chemical equations that stoichiometric calculation is conducted.

The key to the success of this sequence will be the care with which the macro phenomena for study are selected and the submicro representations to be used arrived at.

6.3 Selection of Macro Phenomena and Representations

6.3.1 Macro Phenomena

In a previous section, two similar practical activities involving the combustion of magnesium were proposed. One was the observation of the appearance of magnesium and its product after combustion, and to compare qualitatively the changes in mass of the solid before/after the burning; the other involved measuring the exact mass of magnesium and magnesium oxide so that stoichiometry between the reactant and the product can be inferred or verified.

In conducting a practical activity that aims at the learning *of* science, it is essential that students could easily identify good results so that their learning of the target concept can be supported (Hodson 1993). We note it is unlikely that the combustion of magnesium in the school laboratory could yield good results that support the learning or verification of stoichiometry. Some of the magnesium may remain unreacted, while some materials may escape from the crucible where the combustion takes place. Indeed, the results of this activity have been known to be so inconsistent that it has been used as a critical incident for teachers' decision making (in Nott and Wellington 1998). Therefore, quantitative study of the exact mass relationship between magnesium and magnesium oxide does not seem to be a recommendable activity in the learning of stoichiometry.

Some students hold the preconception that residues from burning are lighter than their reactant. The combustion of magnesium can be framed as a cognitive conflict activity. Students are asked before the activity their expected change in the mass (unchanged, increased, or decreased) of the piece of magnesium after combustion. It is likely some students would predict that the mass would decrease after burning. The increase in mass would be contradictory to some students' preconception and constitute a cognitive conflict that demands explanations alternative to their prior understanding (Limón 2001). Given the spectacular observable changes, it is likely that simply having students experience the phenomena of combustion and measuring the mass of the piece of magnesium and the mass of the product would be useful in motivating students and to prepare them for a submicro explanation of the reaction.

6.3.2 Submicro Representation

A major difference between the two particulate diagrams (proposed in Fig. 6.1 at point (5) and the description in point (6) on p. 4) is the number of particles represented. These two diagrams may fit into the idea of single-particle diagrams and many-particle diagrams respectively (Bucat and Mocerinob 2009). In general, a single-particle diagram, i.e., a diagram showing a single molecule, would be sufficient to represent ideas such as the stereostructure of molecules and bond angle of certain atoms/groups. Some ideas, such as melting, boiling, dissolution, states of matter, equilibrium, strength of ionic substances and metals, cannot be meaningfully represented by single-particle diagrams. Rather, they have to be represented through a collection of the particles that are involved in the process. Based on their investigation of how students visualized chemical reactions, Ben-Ziv and colleagues (1987) suggested that some of students' misunderstanding of chemical reactions related to textbooks' misuse of single-particle diagrams in representing ideas that should have been done with many-particle diagrams.

We postulate that the single-particle diagram (in Fig. 6.1) may not support learners' translation of the submicro representation into a chemical equation. Particularly, its convention does not differentiate when to represent the number of particles as a stoichiometric coefficient (as 2Mg rather than Mg_2) and as a subscript (O_2 rather than 2O). As some students have confusions about the two numbers (e.g., Sanger 2005), the single-particle diagram that may create the confusions should be avoided. Moreover, the single-particle diagram does not give students any hints about the physical states of the substances involved in the reaction. We are aware that such hints (i.e., the random spread of particles far apart to represent a gas, regularly and closely arranged particles to represent a solid) are themselves conventions and they may not be apparent to students. Yet such conventions are the representations that we expect students to learn. Therefore, the many-particle diagram should better support students' understanding of the macro phenomena of burning magnesium.

6.3.3 Symbolic Representation

We have proposed that a many-particle diagram would better be used as a submicro representation of the combustion. We would suggest that the same diagram should also serve as a bridge to the formulation of a chemical equation. Given that some students were known to have difficulties in writing a chemical equation based on particulate diagrams (Nurrenbern and Pickering 1987; Sanger 2005), teachers should support students' translation of the diagram to the equation. Such a support includes counting the number of magnesium atoms, oxygen molecules and the number of formula unit of magnesium oxide in the diagram with the students, which would then lead to the simplest ratio of these entities and hence the equation $Mg + O_2 \rightarrow 2MgO$. This stage of the teaching should focus on the translation from the number of submicro entities from the many-particle diagram into a balanced chemical equation. We propose that the physical states of the chemicals may not be necessary at this moment. An inclusion of the state symbols simultaneously may confuse students about whether the focus should be on the macro phenomena or the many-particle diagram. It is envisaged that the physical state should be included only when the teacher would link the equation to the macro phenomena.

6.4 A Sequence for Introducing Stoichiometry

It is suggested that the following activities or representations in sequence should be likely to facilitate students' learning of introductory stoichiometry:

(1) Observation of the burning of magnesium, and the prediction of the changes in mass of magnesium and its combustion product;
(2) A many-particle diagram representing the submicro entities involved in the chemical reaction. The cognitive conflict (that the mass of the product is less

than that of the magnesium) may be resolved by focusing on the number of magnesium ions and oxide ions produced from the given number of magnesium atoms.

(3) The balanced chemical equation of the reaction is derived from the many-particle diagram. State symbols are added subsequently when teachers intend to draw students' attention to the linkages of the equation and the macro phenomena.

It is envisaged that such a teaching sequence would offer students meaningful experience for a mathematical manipulation of the exact mass relationship between the reactants and product. This sequence was trialed, as is shown in the following two sections.

6.4.1 *Background of the Lesson and Students' Prior Learning*

This section describes and then analyzes a chemistry class in which the teacher introduced the idea of stoichiometry. The teacher has around 10 years of teaching experience. We collaborated with the teacher in a project that aimed at developing teachers' competence in teaching chemistry with respect to the macro-submicro-symbolic relations. Before the lesson, the first author of this chapter discussed with teacher our proposed teaching strategies, which is presented in the earlier part of the chapter. The teacher indicated she would use it in her teaching of stoichiometry.

The class was Year 10 (15–16 years old) students in Hong Kong. It had around 30 students; with roughly an equal number of male and female students. Based on the teacher's estimation of students' performance in territory-wide public examinations, the students were at around the 50th percentile among Hong Kong student population.

Before the students were introduced stoichiometry, they had been taught the idea of the mole, and its relationship with the mass and the molar mass of substances. In those lessons, students worked on various problems typical of mole calculation, e.g., given a certain amount of copper (in grams), how many copper atoms are there? Given a certain amount of water (in moles), what is its mass? Given a certain mass of glucose, how much glucose (in moles) are there? Other than these typical problems,

(1) the teacher would like the students to have a perceptual feel of the abstract mathematical manipulation. So the students were shown the corresponding amount of substances before they embarked on the calculation. For example, they were shown the exact amount of copper before they calculated the number of copper atoms in the sample. In some tasks, students would have to weigh a certain amount of water. Such activities aimed to help students to link up their symbolic manipulation with the corresponding macro phenomena.

(2) In order to facilitate conceptual understanding rather than merely algorithmic manipulation, students were challenged with some questions that demanded

reasoning of the relationship between number of particles and mass (Stavy and Rager 1990). For example, they were asked whether there were a same number of atoms in 1 g of gold and 1 g of silver. And if they do not have the same number, which sample, 1 g of gold or 1 g of silver, would have more atoms?

During the class time, students were keen to work on the tasks. Video clips (with English subtitles) of the lessons are available at the Internet.[1]

6.5 A Description of the Lesson

In the chemistry lesson that we describe here, the focus is on the way the teacher introduced students the concept of stoichiometry, i.e., a conceptual understanding of the quantitative relationship between the mass of reactants and products in chemical reactions. In the teaching, a submicro representation of a chemical reaction was utilized. We are aware that some students faced considerable difficulties in mathematical manipulation, e.g., handling scientific notations. The aim of the lesson was not to tackle this problem. Rather, the focus was on fundamental concepts of stoichiometry.

Before the lesson to be described here, students had burned magnesium and observed magnesium and magnesium oxide. At the beginning of the lesson, the teacher reminded the class they had the experience of burning magnesium and that there was some white ash (without the name of the ash mentioned) left behind.[2] She asked whether they thought the ash was heavier or lighter than the piece of magnesium. A class vote (through students raising their hands) was conducted to elicit students' views. Half of the students opted for 'heavier', while the other half opted for 'lighter'. The teacher did not tell them immediately that it was heavier. Rather she told the students that the lesson was going to answer that question. She added that,

> "Different people have different views. Some think that it becomes lighter. Some think that it becomes heavier. Ask yourselves for the reasons. What are the reasons for being 'lighter' or 'heavier'?"

She also mentioned the burning of paper as an example to illustrate that there were reasons to believe that the product of burning magnesium was lighter than the metal. After that, she showed students a YouTube video of the combustion of magnesium. Her focus was the macro phenomenon of the formation of a white residue,

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[1] Please click the button "Mole" in the left hand side of the page: http://web.edu.hku.hk/knowledge/projects/science/qef_2010/d6/main.html

Episodes of the lessons can be found from "Macro: Is 1 g Ag or 1 g Au heavier?" to "Empirical nature of science"

[2] Episodes of the lesson is available at: http://web.edu.hku.hk/knowledge/projects/science/qef_2010/d6/6c13_probe_S_idea.html

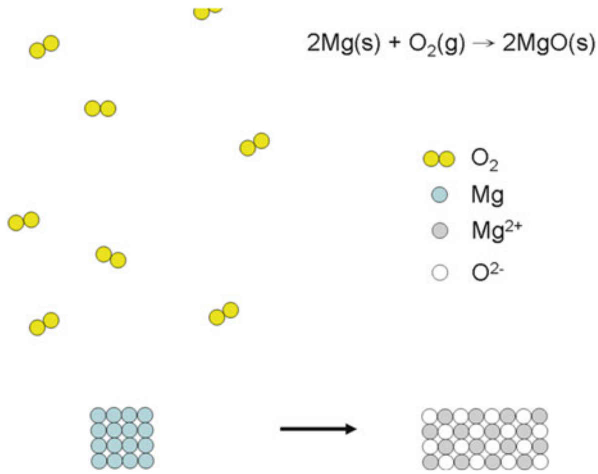


Fig. 6.3 A submicro representation of the reaction between magnesium and oxygen with the formation of magnesium oxide

called magnesium oxide. Then she explicitly stated her intention that she wanted students to think about what happened at the submicro level,

> "… this is what you can see in reality; but if we think about what has happened inside the sample, what actually has happened to the particles?"

After posing the question, the teacher showed the class the following diagram through an LCD projector (Fig. 6.3).

Immediately she drew students' attention to the particulate diagram. Whilst pointing to the corresponding parts of the diagram, she told the class the meaning of those particles:

(1) The yellow circle pairs represented oxygen gas. As she pointed to the space with yellow circle pairs, she linked to the YouTube video:

"Those yellow balls are oxygen gas. Obviously just now when it burned, there's a lot of oxygen nearby. There's a lot of air, isn't there?"

(2) The array of light blue circles represented magnesium metal.

(3) The array of alternating white and grey circles to the right of the arrows represented magnesium oxide:

What did they [while pointing to the block of light blue circles with the mouse pointer] finally become? A student just told me a moment ago that it was… 'magnesium oxide' [answered many students] …this pile of product. They are ionic bonding arranged in a regular pattern. They are in regularly layered, crystal arrangement.

After explaining the meaning of the diagram, the teacher referred to the equation in the top right hand corner and said,

> If you're asked to write… a chemical equation, the one at the top right hand corner. You'll express that it's a reaction between magnesium (while moving the mouse pointer over the term 'Mg' in the equation and then the block of light blue circles) and oxygen (while moving the mouse pointer over the term 'O_2' in the equation and then the space where the

yellow circle pairs scattered). Then it becomes magnesium oxide (while moving the mouse pointer over the term 'MgO' and the block of grey and white circles), this pile of magnesium oxide.

In this part of the talk, the teacher did not mention the stoichiometry of the reaction. Rather, she just focused on the relationship between the submicro representation and the equation. Then she further highlighted the variety of ways that a chemical reaction could be represented,

… in this process, we can, if you like, use the chemical equation to represent what is happening. Your observation of this experiment was like that. But you can also think about what actually has happened inside by taking a microscopic perspective.

It was only after the teacher had emphasized the multiple ways of representing the reaction that she started to deal with the quantitative aspect. She counted with the students the number of 'atoms' participated in the reaction in the light of the submicro representation. The way she dealt with oxygen is reported here.

Teacher: How many "O" are there?
Students [in echo]: Sixteen.
Teacher: There are 16 "O". Yes. There are 16 "O". How many O_2 are there?
Student: Eight.
Teacher: Eight O_2 molecules, that means there are 16 "O" atoms.

Similar question and answer interactions were conducted for the number of magnesium atoms involved and the number of magnesium and oxide ions formed. After ascertaining students' interpretation of the submicro representation, the teacher asked again whether the product should be lighter than the magnesium metal. There was an echo from students that the product became "heavier".

6.6 Some Notes on the Lesson

6.6.1 Cognitive Conflict

It was noted that cognitive conflict as a teaching strategies should not be taken as a single variable that determines students' success in learning. Among many other factors, it is essential that the problems or the anomalous data presented must be intelligible and relevant to students. Students must also have the reasoning abilities to solve the conflict (Limón 2001). As some students might think matters 'vanished' after combustion, the question of whether the product would be heavier or lighter than the magnesium challenges students' existing belief that the 'ash' would be lighter. It is observed the class was very active in giving responses to the questions. The students were willing to participate in the class vote; some students spoke very loudly their views, which may mean that they were engaged and were confident in their answers.

We have noted that the success of this strategy depends on how teachers interact with the conflict event and students such that students would find a resolution that they are satisfied with and is intended by the teachers (Baddock and Bucat 2008). After the class vote, the teacher did not immediately discuss the scientific view or ask students to defend their preconceptions. Rather, she used the burning of paper to justify how students might believe that the 'ash' was lighter. While the voice of students was not elicited, extensive research in science education has suggested that students tend to apply their daily observation of burning to make sense of similar phenomena, e.g., the combustion of metals. In that sense, the teacher created a safe environment for learning in which students did not have to openly defend their views that the teacher knew would have to be modified in the later part of the teaching. In this way, she was not trying to 'replace' students' views with the scientific view. She acknowledged students' ideas and tried to limit the scope of application of their ideas (Smith et al. 1993/1994). It is likely that the learning environment the teacher created has facilitated students' learning. The students were still very keen to express their options in class vote after the teacher explained the reaction with the use of the submicro diagram. The engagement was evidenced irrespective of the fact that their earlier views were refuted. Watson et al. (1995) reported that some students could disregard their observation that the product became heavier than the magnesium – a merely observation of data did not guarantee conceptual learning. We would propose that the particulate diagram (and the way the teacher discussed with the class about it) might have served as a means through which students have found the resolution of the conflict intelligible.

6.6.2 Representing Macro Phenomena in a Particulate Diagram – Air and Oxygen Gas

The teaching started with a recall of students' experience of the macro phenomena, namely, the burning of magnesium. A video of the burning was also shown. Then, the particulate diagram was presented to the whole class. She made explicitly that the diagram represented 'what actually has happened to the particles'. To help students to understand the notations used in the diagram, she told the class directly that the cluster of yellow circles *are* oxygen gas and referred students to think about the surroundings where the burning happened. In this part of the teaching, it seems that many students were able to grasp at the conventions of the diagram. It was reflected from their responses about the area that represented magnesium oxide. Nevertheless, we notice that the abstraction of 'air' to 'oxygen gas' as macro entities was not addressed in the lesson. In the diagram, only oxygen molecules were represented. We are thus unsure whether such an implicit modelling of air as oxygen gas would hamper students' understanding of the phenomena.

6.6.3 Highlighting Different Representations

Instead of discussing with students the number of submicro entities involved in the reaction in the diagram, the teacher directly showed students the balanced equation. Her focus was to emphasize to students that there could be different ways of representing the combustion of magnesium. At this point, while she intended to foster relational understanding of the triplet, we cannot be sure if the students could meaningfully relate the balanced equation with the number of submicro entities involved in the reaction. Also, it might leave a question about whether students can appreciate why the reaction had to be represented in the form of a chemical equation.

6.7 A Detailed Reading of the Particulate Diagram

A detailed examination of the particulate diagram came in after the teacher showed students the chemical equation. She counted with students the number of particles of magnesium, oxygen and magnesium oxide. After ascertaining the results of the student's counting of particles, she again asked students' view about the relative mass of magnesium and its combustion product. Most of the students expressed the view that the product was indeed heavier. Although the students were not asked for the rationales behind their changes of views, it seems that the particulate diagram has facilitated students understanding of the submicro interaction and a prediction of the increase in mass after the reaction.

The activity overall might seem to have been straightforward and unchallenging to students. In a general sense, it served the function of assessment *for* learning – students' views were probed into and subsequent teaching was conducted based on those views. In the light of the learning occurring with the diagram, the activity did seem to facilitate students' formation of mental representations of the referent that as intended by the teacher. That is, the reaction between 16 magnesium atoms and 16 oxygen atoms that formed 16 formula units of magnesium oxide (as a submicro phenomenon); and the reaction between magnesium metal and oxygen gas with the formation of magnesium oxide solid (as a macro phenomenon). Ensuring a shared or coherent mental representation between students and the teacher is not a trivial or dogmatic demand. Such mental representations would be essential for the development of target knowledge, i.e., stoichiometry of the chemical reaction. It is apposite here to discuss what is entailed in understanding a diagram. Running the risk of over-simplification while maintaining the essence that should guide and inform classroom practice, a model for diagram comprehension (based on Hegarty 2011) is presented in Fig. 6.4.

When students looked at the diagram, their visual senses would attend to its different features and components (called the *Visual features* in the model). It may be different ways the circles were arranged in the diagram, for example, some existed randomly while some existed orderly. It may be the two blocks of circles near the arrow. It may also be those yellow circle-pairs. These *visual features* were encoded as students' *Mental representation of the diagram*, which we hope would become a

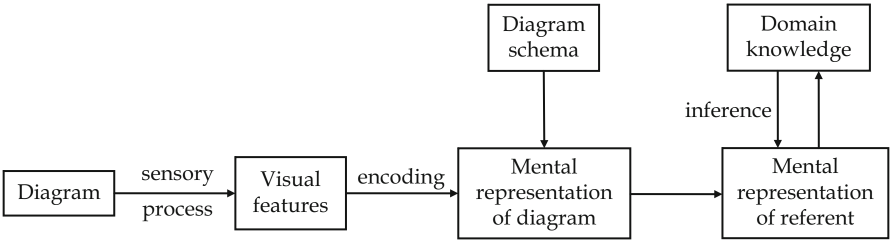


Fig. 6.4 A model for comprehension of diagram (Modified from Hegarty 2011, p. 453)

Mental representation of the referent. It is unlikely that such a diagram is exactly replicated, or copied, in students' minds. In other words, it is unlikely that the mental representations formed by different learners are exactly the same. Different learners encode different objects and different features of the diagram as their *mental representation of the diagram*. The encoding depended on students' understanding of conventions through which submicro entities are represented. For teachers, a pair of connected circles represents a molecule, randomly and spaced out circle-pairs represented the gaseous state, a block of circles connected regularly resting on a line represented the solid state, circles left and right to the arrow represented reactants and products respectively. Such an understanding is called *Diagram schema*. If students lacked the *diagram schema* that was required, comprehension of the diagram would not be possible.

As chemistry teachers, our *mental representations of the diagram* very swiftly – if not instantaneously – become *mental representations of the referent*, which is the reaction between magnesium and oxygen at the submicro level and its stoichiometry. Instead of merely encoding two connected circles as such, they are represented as oxygen molecules in our mental system. Our existing knowledge of the kinetic molecular model allows us to represent the random circle pairs (in the diagram) as some oxygen gas in our *mental representation of the referent*. Similarly, the block of circles on the left to the arrow (in the diagram) are not a block of circles as such, but is solid state magnesium in our *mental representation of referent*.

There is a considerable chance that our expertise in chemistry would blind us from appreciating students' challenges in comprehending meanings carried by the *Visual features* of the diagram. There has been evidence from elsewhere that students did not move beyond the *mental representation of diagrams* and fail to form a *mental representation of referent*. They would interpret a diagram without recognizing what was actually being represented (Bucat and Mocerinob 2009). For example, based on the structural formula of bromobenzene, some students regarded the molecule did not have a plane of symmetry – because "B≠r" (Kleinman et al. 1987). As far as comprehending the submicro diagram is concerned, without prior knowledge, such as that oxygen molecules are made of two atoms (diatomic), that closely and orderly packed circles are a representation of a solid state, and that alternate circles arranged in a block are made of two different types of ions, it is unlikely students would properly comprehend the diagram. Therefore, making explicit the meanings of each of the circles and the meaning of the collection of circles was essential in classroom teaching.

The intended purpose of the submicro diagram went beyond the interaction of the magnesium and oxygen. It also involved the stoichiometric relationship between the reactants and the product, which was the target *Domain knowledge* to be developed by students. Support is needed to engender the knowledge development. It is represented by the arrow pointing to *Domain knowledge* emerging from *mental representation of referent* (in Fig. 6.4). For those who have already possessed this knowledge, they can infer (*Inference* in the model) the stoichiometry relationship from the diagram. Nevertheless, some students may appreciate the intended meaning of the number of circles in the diagram. Therefore, it is important that the teacher counted with students the number of each of these submicro entities, such that students could infer how the mass of the product was different from that of the reactant. It is likely that students' learning of stoichiometry could be better supported if they are more explicitly showed the exact relationship between the diagram and the balanced equation.

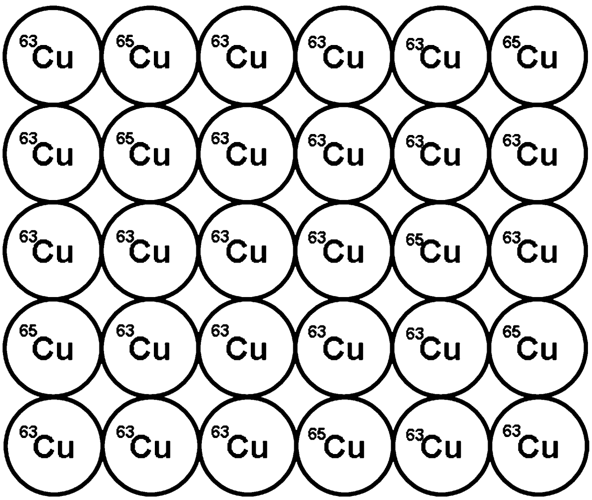
The formation of the *mental representation of referent* involved more than a direct matching of the *mental representation of the diagram* and our *domain knowledge*. It also includes a selection, of which part of the existing knowledge is included and which part to be ignored. For example, although students may be aware of the electron-sea model of metals, as it is not directly relevant in stoichiometry here, they have to screen out this model and regarded metals as a collection of metal atoms. Therefore, having a repertoire of *domain knowledge* is not enough, in understanding a diagram, students have to select the piece of existing knowledge that is relevant to the context such that a *mental representation of the referent* conducive to future problem solving (stoichiometry) can be formed. Such an awareness is not trivial. It points to some possible challenges faced by students and the need for teachers to devise suitable strategies that facilitate students' comprehension of diagrams. In the trial lesson reported above, the explicit reference between the circles and their referents made by the teacher and the explicit counting of the submicro entities might have facilitated students reading of the diagram such that they could tell how the mass of the product has changed after the reaction.

6.8 Conclusion

In this chapter, we have proposed a teaching strategy that introduces stoichiometry to secondary school students. The proposal was developed based on our understanding of some difficulties students faced in learning of macro phenomena (the combustion of magnesium) as an abstraction of daily phenomena, in understanding the idea of mass conservation and in reasoning with submicro and symbolic representations. We suggest that the practical activity in this context should be procedurally straightforward and intellectually challenging enough to be in conflict with students' existing knowledge, yet simple enough so that they can find the resolution intelligible. In this proposed teaching strategy, a submicro representation in the form of a many-particle diagram plays a key role in facilitating students' conceptual understanding of the chemical reaction and its stoichiometry. As far as the macro phenomenon is concerned, the diagram serves as an explanation to the reaction between a piece of magnesium ribbon and oxygen gas, and represents the increase in mass of the product as compared with that of the magnesium. As far as the symbolic representation is concerned, with a careful design of the number of particles in the diagram, it serves to support students working out of the balanced equation of the reaction. That is, the diagram serves as a bridge for the macro phenomenon and a symbolic representation.

The suggested teaching strategy was implemented in a Year 10 classroom. While we are unable to generalize the experience of teaching and learning in a single classroom, we observed that students were engaged in the cognitive conflict activity. The submicro diagram did facilitate resolving the cognitive conflict, which may imply that students were able to associate the submicro representation to the macro phenomenon that they explored. We would like to ascribe students' engagement and learning not by the diagram as such, but by the teacher's effort in making sure that students understood the ways that different components of the diagram represented submicro entities and how they related to their corresponding macro phenomena. It is likely the explicit teaching facilitated students' transformation of different *visual features* of the diagram (i.e., different arrangement of circles) into *mental representations of their referents* (i.e., different submicro entities of the reactants and the product) and possibly students' development of the idea of stoichiometry as the target *domain knowledge*.

The use of particulate diagrams with the sequence of macro-submicro-symbolic representations has been extended to the teaching of different types of chemical reactions. In a similar way, the introduction of the idea of isotopes and the calculation of relative atomic mass can be supported by the following diagram (or a diagram with less copper atoms):



Like the teacher we discussed in this chapter, we suggest that teachers may first ascertain students' understanding of the diagram as a representation of a part of a piece of copper metal, and students' understanding of the symbols ^{65}Cu and ^{63}Cu. Instead of starting with abstract formula or drilling of algorithms, teachers may work with students the number of ^{65}Cu and ^{63}Cu atoms and then figure out the relative atomic mass of copper based on the diagram. In short, this chapter proposes the use of particulate diagrams in supporting students' linking of submicro representations to macro phenomena and symbolic representations.

References

Abrahams, I. (2011). *Practical work in secondary science: A minds-on approach.*. London/New York: Continuum.

Aikenhead, G. S. (1996). Science education: Border crossing into the subculture of science. *Studies in Science Education, 27*, 1–52.

Alexander, M. D., Ewing, G. J., & Abbott, F. T. (1984). Analogies that indicate the size of atoms and molecules and the magnitude of Avogadro's number. *Journal of Chemical Education, 61*(7), 591.

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

Baddock, M., & Bucat, R. (2008). Effectiveness of a classroom chemistry demonstration using the cognitive conflict strategy. *International Journal of Science Education, 30*(8), 1115–1128.

Ben-Zvi, R., Eylon, B.-S., & Silberstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education, 63*(1), 64–66.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1987). Students' visualization of a chemical reaction. *Education in Chemistry, 24*(July), 117–120.

Bucat, B., & Mocerinob, M. (2009). Learning at the sub-micro level: Structural representations. In J. K. Gilbert & D. Treagust (Eds.), *Multiple representations in chemical education* (pp. 11–29). Dordrecht: Springer.

Cheng, M. M. W. (2013). Learning from students' performance in chemistry-related questions. In A. S. L. Wong (Ed.), *Learning from times 2007: Implications for teaching and learning science in Hong Kong*. Hong Kong: The Government of the Hong Kong Special Administrative Region.

Cheng, M. M. W., & Gilbert, J. K. (2009). Towards a better utilization of diagrams in research into the use of representational levels in chemical education. In J. K. Gilbert & D. Treagust (Eds.), *Multiple representations in chemical education* (pp. 55–73). Dordrecht: Springer.

Cracolice, M. S., Deming, J. C., & Ehlert, B. (2008). Concept learning versus problem solving: A cognitive difference. *Journal of Chemical Education, 85*(6), 873–878.

Gabel, D., & Sherwood, R. D. (1984). Analyzing difficulties with mole-concept tasks by using familiar analog tasks. *Journal of Research in Science Teaching, 21*(8), 843–851.

Gilbert, J. K., & Treagust, D. (Eds.). (2009). *Multiple representations in chemical education*. Dordrecht: Springer.

Gilbert, J. K., Reiner, M., & Nakhleh, M. (Eds.). (2008). *Visualization: Theory and practice in science education*. Dordrecht: Springer.

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.

Hegarty, M. (2011). The cognitive science of visual-spatial displays: Implications for design. *Topics in Cognitive Science, 3*(3), 446–474.

Hill, G. C., Holman, J., Lazonby, J., Raffan, J., & Waddington, D. (1989). *Introducing chemistry: The salters' approach*. Oxford: Heinemann Education.

Hodson, D. (1993). Re-thinking old ways: Towards a more critical approach to practical work in school science. *Studies in Science Education, 22*, 85–142.

Jaber, L. Z., & BouJaoude, S. (2012). A macro–micro-symbolic teaching to promote relational understanding of chemical reactions. *International Journal of Science Education, 34*(7), 973–998.

Johnstone, A. H. (1982). Macro- and microchemistry. *School Science Review, 64*(227), 377–379.

Johnstone, A. H. (2010). You can't get there from here. *Journal of Chemical Education, 87*(1), 22–29.

Kleinman, R. W., Griffin, H. C., & Kerner, N. K. (1987). Images in chemistry. *Journal of Chemical Education, 64*(9), 766–770.

Koch, H. (1995). Simplifying stoichiometry. *The Science Teacher, 62*(8), 36–39.

Limón, M. (2001). On the cognitive conflict as an instructional strategy for conceptual change: A critical appraisal. *Learning and Instruction, 11*(4–5), 357–380.

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: A central problem in secondary science education* (pp. 283–294). Utrecht: CD-[Beta] Press.

Nelson, P. G. (2002). Teaching chemistry progressively: From substances, to atoms and molecules, to electrons and nuclei. *Chemical Education Research and Practice in Europe, 3*(2), 215–228.

Nelson, P. G. (2013). What is the mole? *Foundations of Chemistry, 15*(1), 3–11.

Nott, M., & Wellington, J. (1998). Eliciting, interpreting and developing teachers' understandings of the nature of science, science and education. *Science & Education, 7*(6), 579–594.

Nurrenbern, S. C., & Pickering, M. (1987). Conceptual learning versus problem solving: Is there a difference? *Journal of Chemical Education, 64*(6), 508–510.

Risch, B. (2010). *Teaching chemistry around the world*. Münster: Waxmann.

Sanger, M. J. (2005). Evaluating students' conceptual understanding of balanced equations and stoichiometric ratios. *Journal of Chemical Education, 82*(1), 131–134.

Smith, J. P., diSessa, A. A., & Roschelle, J. (1993/4). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *The Journal of the Learning Sciences, 3*(2), 115–163.

Stavy, R., & Rager, T. (1990). Students' conceptions of the three dimensions of the quantity of matter – volume, mass and number of particles. In P. L. Lijnse, P. Licht, W. de Vos, & A. J. Waarlo (Eds.), *Relating macroscopic phenomena to microscopic particles: A central problem in secondary science education* (pp. 233–246). Utrecht: CD-[Beta] Press.

Stieff, M., Ryu, M., & Yip, J. C. (2013). Speaking across levels – generating and addressing levels confusion in discourse. *Chemical Education Research and Practice, 14*(4), 376–389.

Taber, K. S. (2001). Building the structural concepts of chemistry: Some considerations from educational research. *Chemistry Education Research and Practice in Europe, 2*(2), 123–158.

Taber, K. S. (2002). *Chemical misconceptions – prevention, diagnosis and cure: Volume 1: Theoretical background*. London: Royal Society of Chemistry.

Taber, K. S. (2009). Learning at the symbolic level. In J. K. Gilbert & D. Treagust (Eds.), *Multiple representations in chemical education* (pp. 75–105). Dordrecht: Springer.

Taber, K. S. (2013). Revisiting the chemistry triplet: Drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education. *Chemical Education Research and Practice, 14*(2), 156–168.

Talanquer, V. (2011). Macro, submicro, and symbolic: The many faces of the chemistry 'triplet'. *International Journal of Science Education, 33*(2), 179–195.

Treagust, D. F., & Chandrasegarana, A. L. (2009). The efficacy of an alternative instructional programme designed to enhance secondary students' competence in the triplet relationship. In J. K. Gilbert & D. Treagust (Eds.), *Multiple representations in chemical education* (pp. 151–168). Dordrecht: Springer.

van Lubeck, H. (1989). How to visualize Avogadro's number. *Journal of Chemical Education, 66*(9), 762.

Watson, R., Prieto, T., & Dillon, J. S. (1995). The effect of practical work on students' understanding of combustion. *Journal of Research in Science Teaching, 32*(5), 487–502.

Yarroch, W. L. (1985). Student understanding of chemical equation balancing. *Journal of Research in Science Teaching, 22*(5), 449–459.

Part III
Teachers' Use of Visual Representations in Culturally-Diverse Classrooms

1.1 Introduction

This part is concerned with the implications of language and cultural setting, severally and jointly, for teachers' selection and use of visual representations in science education. It consists of four papers.

The first, by de Vries and Ashraf (this volume, Chap. 7) is solely concerned with the cultural issue. This focus is sharpened in two ways. First, by looking at practice in France and Pakistan, two countries that are very different in all respects: their schools, universities, teacher background selection and education. Second, by looking at practice in two subjects that are well separated in the curriculum in both countries: physics and geography. The work was conducted by examining four textbooks, two on each subject and in each country, and by interviewing five experienced teachers of each subject in each country.

Most helpfully, the chapter provides a review of the literature concerning the three ways in which visualisations can be classified, that is, in terms of: their graphical form, the subject domain where they are used, their pedagogic function. The inquiry sought information on teachers' awareness of the different types of visualizations, the frequency of the presence of these types in textbooks, and any indications of a cultural dependence of their manner of use.

The absence of any internationally agreed convention on a terminology of types for visualisations was reflected in the widely different vocabulary in use across these countries and domains. On one thing all the teachers were agreed: visualisations should not serve a merely decorative function in textbooks, although we do wonder whether the graphic designers employed by publishers would agree with this view. However, on two matters there was a sharp cultural divide. First, the use of the various types of visualisations in textbooks varied markedly both between the subjects and between the countries. Second, in the matter of pedagogic function, there was a marked cultural difference between the two countries, irrespective of subject domain: in Pakistan, students were just required to memorise visualisations, whilst in France the emphasis was on an understanding of the information represented, a process encouraged by accompanying each visualization with problems/exercises for the students to tackle.

The second chapter, by Waldrip, Satupo and Rodie (this volume, Chap. 8), is also focused on cultural issues, but the language element is touched upon. In this case, the contrasts are drawn in respect of representational practice between a developed country (Australia) and that broad sweep of cultures found in Melanesia and Indonesia. As it is practice in the later contexts that will be novel to most readers of this volume, it is that aspect of the chapter, derived from a broad programme of survey, interview and classroom observation, that is concentrated on in this brief Introduction.

In Melanesia and Indonesia, the primary purpose for school education is the maintenance of social harmony. In practice, this means that the teacher is expected to be an expert whose knowledge is not to be challenged, with the social position and classroom authority of male teachers being stronger than that of female teachers. This does mean that constructivist teaching, with its expectation of the temporary suspension of the display of teacher expertise, is hard to adopt. The prevailing ethos of social harmony results in students from higher social backgrounds being expected to do well and being shown deference by other students, irrespective of their actual performance in class, a situation which would seem to make the attainment of high standards of learning difficult to attain.

The Melanesian and Indonesian students valued prepared 'official' representations, which they expected to memorise perhaps rather than understand. Their teachers, on the other hand, saw the value of student-developed representations produced in the local language, not least because their use, mainly verbal, could overcome students' lack of knowledge of the language of formal education (often English), their lack of experience with the artefacts of science, and because of the general lack of prepared resources for representation. Teachers drew heavily on students' prior experience in supporting the development of these representations, invoking drama, story-telling, and the use of analogy, in their evolution, these having a positive effect on student engagement. The link between science and the real world of the students was valued, whilst teachers saw the student-generated representations as a way of gaining entry into student thinking.

The third chapter, by Mammino (this volume, Chap. 9), is an in-depth analysis of the interplay between language and representation, arising from the experience of teaching chemistry at university level for 15 years in contexts of severe social and educational under-privilege. The core argument put forward is that the uses of language and of representations in science education (and more generally) are interdependent: a full understanding of ideas requires the mastery of the semiotics, the syntax, and the semantics of both language and representation. This thesis was initially developed in the writing of textbooks, where careful consideration had to be given to the design of representations, the language of the text, and the captions used to enable the two to best convey understanding.

The major part of the chapter is devoted to case studies of the problems that arise when the topics of Boyle's Law, Oxidation Number, Gas Isotherms, the Carnot Cycle, and Reaction Concentrations, are taught in remedial classes to undergraduates who should have mastered them at school level. The adoption of a teaching method that relied on the extensive use of questions and answers, together with student creation of representations, enabled the problems that students have in attaining understanding to be identified. The expression by students of a wide variety of misconceptions enabled the implications of an inadequate gasp of the language of instruction (here English and usually students' second or third language) to become apparent. At the same time, students showed great weakness in understanding of the principles on which representations were or could be constructed. The outcome was poor understanding resulting from the interplay of these two sources of weakness. An improvement in learning was attained as both language and representation were iteratively improved.

There were three cultural issues that underlay the language/representation issues outlined above. The first was a lack of manual dexterity on the part of the students: they could not draw coherent representations. The second was the strong preference of the students to passively memorise representations: learning by rote was universal in these classes. The third was the evidence that gradually emerged of poor science teacher quality at school level. These three issues, together with the evidence of poor performance from the case studies, strongly suggest that the problems identified have complex cultural roots.

Whilst the other three chapters take a view of 'culture' as being concerned with the development of knowledge and understanding in schools, the fourth chapter, by Gilbert and Afonso (this volume, Chap. 10), takes a broader view, one that is concerned with the entire population including school children. The focus is on chemical ideas and the locus of attention is the 'popular book', one that is designed to have a general appeal. Such books, freed from the traditions of textbooks, take broad views on chemical knowledge and how it may be learned.

It is argued that well-designed representations with a clear role in relation to the text have much to offer such books. To illustrate how this might be done, case studies are presented of two popular books: one directly appealing to everyday concerns and the other also of possible interest in relation to formal chemical education. They were both found to adhere to good practice, with the representations supporting a strong textual narrative that is likely to encourage sustained engagement by the reader, whether casual or within the formal educational system. Two caveats were noted: a wide range of possible themes for such books exist and only a few of these have been exploited; there was a complete lack of any use of mathematical models in either of the books, this recognising and reinforcing the cultural isolation of mathematics.

Chapter 7
Teachers' Thoughts on Visualisations in Diverse Cultural Settings: The Case of France and Pakistan

Erica de Vries and Muhammad Ashraf

Abstract Visualisations gain more and more importance in pedagogical material, in text books and in computer programs. Despite the co-existence of many different types of visualisations or graphical *genres*, learning research only has taken into account the distinction between text and pictures. The current study aims at unpacking what, at least in learning research, seems to be one single holistic indivisible category of visualisations. The presented approach focuses on teachers' thoughts on the existence of different types of visualisations and their presumed function in teaching and learning. Ten teachers from two different countries, France and Pakistan, and from two different subject matters, physics and geography, were interviewed. Amongst others, results showed that teachers are confident about student comprehension for generic categories such as tables, line graphs, and maps. However, the transparent nature of hybrid visualisations was called into question. This is an important finding given the fact that technological means have considerably enlarged the spectrum of visualisation possibilities.

Keywords Physics • Geography • Textbooks • France • Pakistan • Visual representatins • Immediacy • Graphicacy • Educational system – classification of graphical representations • Pedagogical function

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7.1 Introduction

Visualisations are widely used in everyday life, in professional practice, in science and technology, as well as in teaching and learning. Indeed, graphical, as opposed to textual, ways of information presentation gain more and more importance in pedagogical material, schoolbooks and in computer programs for learning. Three viewpoints seem to have become particularly pervasive.

The first one is the idea itself that visual media are increasingly important in today's society. This viewpoint is also known as the visual or *pictorial turn* (Mitchell 1994). Despite its appeal, some authors also criticized this idea pointing out that, in fact, there have been visual turns continuously throughout history. In any case, a noticeable increase of graphics can be observed in Western schoolbooks as well as in learning technologies. A thorough reflexion on the role of such a visual turn in pedagogical material could well be informed by a comparison of non-Western and Western school systems that vary in their susceptibility to this visual turn.

The second viewpoint is that information presentation within the visual medium mainly hinges on *resemblance* relations. Pictures are thought to represent by virtue of the visual similarity between the representation and what is represented. This is in contrast with language or text which is thought to represent by virtue of convention. The opposition between resemblance (natural relation) and convention (arbitrary relation) goes back to the debate in Cratylus on the justification of the choice of words to designate things. Furthermore, the distinction traces back to one of Peirce's triples, namely the three types of signs: icons (similarity), symbols (convention), and indices (contiguity). However, it would be extremely oversimplifying to equate graphics and resemblance on the one hand, and text and convention on the other. The dichotomy might well fall short in describing the observed variety of graphical formats, and moreover does not do justice to the complexity of semiosis as meaning making. As Rastier (2000) noted, the only way to establish the type of relation between a representation and that which is represented is through inspection of an *instance* of a semiotic process. As an example, a picture of dog might evoke a dog or evoke the concept of loyalty; in the first case it would be by virtue of a resemblance relation, in the second by virtue of convention. Many have in fact argued that meaning making from graphics is not solely based on resemblance relations (Goodman 1976; Eco 1976; Wittgenstein 1993). In today's pedagogical material, as we will see below, the existence of different graphical genres or languages with different mixtures of similarity and convention for meaning making is commonplace. Schoolbooks and computer programs contain a variety of graphics and their particular format, or the way in which they should be interpreted, is rarely specified. We therefore propose to more closely study actual authentic visualizations used in textbooks and put them in relation to "pure" categories as described in the domain of information visualization.

According to the third viewpoint, related to the resemblance assumption, visual media possess *immediacy*. Compared to text, visualisations are acclaimed for their transparency, their concreteness, and their support for perceptual inferences (Larkin and Simon 1987). Because of the assumed resemblance relations, the meaning of graphical material is thought to be instantly available without any interpretive activity. According to this widespread belief, graphics such as pictures, graphs, and diagrams are transparent. This also leads to the idea that understanding the graphical medium does not necessitate any interpretive skills. However, maybe well-designed general purpose everyday graphics do not need any thorough interpretative skills, many domain-specific complex graphics do require extensive training and/or experience. In that case, the flipside of the coin is the need for particular skills or experience. Thus, just like reading and writing for texts, the ability to interpret and to construct visualisations seems to be an important skill. Roth et al. (2005) even argue for the necessity of developing "critical graphicacy", i.e. the ability of constructing and deconstructing inscriptions, in other words to disentangle form, content, and purpose of representations (see also MRC, diSessa 2004). Moreover, one may consider educational settings to be a special case of communicational situations characterized by a knowledge disparity between participants. It begs the question of domain-specificity of visualizations within teaching and learning. For example, physics and geography might contain a different balance of the symbolic and the iconic modes of signification. We therefore are highly interested in soliciting the views of teachers from different subject matters.

Those three viewpoints motivated the idea to investigate teachers' thoughts on educational graphics. Differences in the availability of visualizations justify an international comparison, in our case between France and Pakistan. The great variety of graphics in schoolbooks as well as the multiplicity of the signification modes in play warrant the study of authentic graphics and their function in teaching. These functions may well go beyond just "showing" and "transmitting" content, or in Coleman's terms, go beyond merely drawing attention to whatever graphics are available: "Simply pointing to or referring to graphics is not a teaching practice sufficient to help students" (Coleman 2010, p. 216). Finally, the immediacy principle, and the knowledge disparity in teaching and learning situations suggest the value of investigating graphics from both physics, supposedly more convention-oriented, and geography, supposedly more resemblance-oriented.

7.2 An International Comparison Between France and Pakistan

France and Pakistan are different from every point of view. France is a stable well-developed country whereas Pakistan is an under developing third world country with a lot of political and economic problems. France has a unique education system; Pakistan has an education system which is partially borrowed from the English school system. According to the World Bank 2010, France is spending 5.9 % of its GDP expenditures on education whereas Pakistan's expenses on education are only 2.7 % of GDP. The performance of the French system is measured by the Pisa ranking (ranked 22nd, PISA ranking 2009), Pakistan does not participate in these evaluation methods.

Although France has a secular education system, i.e. there is no religious education in the curriculum, students get 1 day off every week to take religious education outside the school (Directorate General for Schools 2010). Pakistan's official religion is Islam, and religious education is compulsory in the school curriculum. There are five levels in the educational system of Pakistan: primary (grades 1–5); middle (grades 6–8); high (grades 9 and 10); intermediate (grades 11 and 12, leading to a Higher Secondary School Certificate); and university programs leading to undergraduate and graduate degrees programs. On the other hand, the French educational system contains three levels (DGS 2010), level 1 (*premier degré*: nursery and elementary schools), level 2 (*second degré*: lower secondary *collèges* and upper secondary general, technological and vocational *lycées*), level 3 (higher education: university education). The French constitution states that it is the duty of the state to provide free compulsory education for all children. France has both public and private schools, but even private schools have a contract with the state. Although, school education in Pakistan is free too and the state provides textbooks to students, the parents have to pay a small amount of money every month. The state has a very low level of control over private schools. Lynd (2007) and DGS (2010) stated that 31 % of students attend private schools in Pakistan whereas only 17 % of the students in France.

In Pakistan, most of the teachers working in public schools have at least a bachelor's degree in their teaching domain, and additionally, they have 1 year of professional education either by attending a teacher training institute or by distance education. However, teacher training is not obligatory for teachers in private schools (Lynd 2007). Lapostolle and Chevaillier (2011) stated that the French teacher education system is unique as compared to other European countries. Until the recent 2010 reforms in teacher education, the Ministry of Education used to recruit Bachelor's degree holders and provide 2 years of training in French teacher training institutes (IUFM). The first year was devoted to prepare for a national competitive exam for recruitment as a teacher and the second year to professional teacher training. Since 2010, some major reforms took place: the academic requirement increased from a Bachelor's degree to a Master's degree for all teachers; universities are now in charge of initial teacher training; teacher training institutes (IUFM) merged into the universities. Further training, after obtaining a master, will be in-service teacher training by the Ministry of education upon recruitment. This change has brought many questions about the competencies of new teachers who will start teaching with almost no practical teacher training. Cros and Obin (2003) mentioned that the salary of French teachers is quite unattractive as compared to other jobs in the country. Young graduates therefore prefer to work in the private sector. Particularly in primary education, the majority of the teachers graduated in humanities. The vast majority of French teachers are females and there is no policy for a gender balance approach because it is unconstitutional to recruit gender wise.

AID (2006) stated that teaching and general performance of teachers in Pakistan has been weak. Teacher training programs run by the government were not able to improve the teaching skills of teachers so as to increase students' acquisition of knowledge. Several explanations have been coined. First, domain knowledge is poorly articulated with teaching strategies. Teacher training mainly focuses on theory and the practical aspects of pedagogy are neglected. Second, teachers hardly use learning aids and are not motivated to use even the low cost aids or any other modern equipment to enhance student learning. Teachers administer classes following a typical lecture method based on the textbooks provided by the state and demanding low levels of student participation. The performance of teachers is monitored by their Annual Confidential Reports (ACRs). Finally, teachers are obliged to take part in many non-educational tasks e.g. election duties or vaccination programs. The state acknowledges these issues and policies are continuously prepared to tackle them i.e. improving teacher training programs, recruiting high qualified teachers on merit basis, etc. Whereas Sarwar and Hussain (2010) stated that the main subjects taught during the teacher training programs in Pakistan are: educational psychology, teaching strategies, foundations of education, educational administration and supervision, curriculum development, and educational measurement and evaluation. Teacher trainers themselves generally lack the experience of teaching in schools; thus teacher training is more theoretical than practical. Geography and physics teachers do not get particular teacher training based on the content domains.

French teachers often select, organize and construct their own teaching material, whereas Pakistani teachers use textbooks which contain mostly text, some tables, and very few maps (geography) and diagrams (physics). In France, there is no specific training about teaching with graphical representations. Geography teachers have the advantage of dedicated training in constructing and interpreting graphical representations as a core part of geography. Physics teachers have the advantage of domain-specific knowledge of scientific graphics, i.e. diagrams, schemas, and the like.

7.3 The Visual Medium as an Educational Toolbox

If we take it that resemblance, spontaneity, intuitiveness, and immediacy are not the only rules governing visual material, we should start by trying to distinguish educationally relevant categories of graphical material. To begin with, very diverse systematic taxonomies of visualisations would be possible depending on the particular classification criteria adopted: graphical form, pedagogical function, signification mode, or nature of the projection of world to visualisation. In this section, we alternatively classify according to form, content, and function.

7.3.1 Classifying According to Graphical Form

A classification according to the form of visualizations follows an objectivist viewpoint that there must be some specifiable relation between aspects of the represented and the representing world (see also Palmer 1978). The objectivist viewpoint is also present in Tufte (2001, p. 13) who stated that the graphic display is the art of presenting complex information with clarity, precision and efficiency. According to Tufte, a graphic representation is thought to serve four purposes: description, exploration, tabulation, or decoration. The representational properties of the graphical medium have been extensively described in Jacques Bertin's Semiology of Graphics (1983) as one of the most renowned and foundational works in the domain of

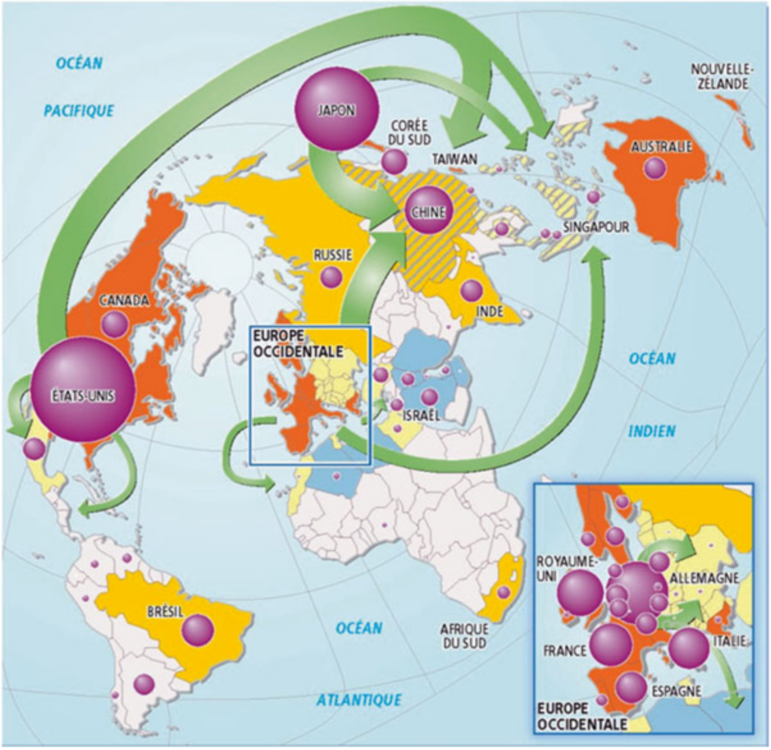


Fig. 7.1 A map in a French geography textbook (Jalta et al. 2004, p. 24. © Editions Magnard)

graphic designing and cartography. As the most important functions of graphics, Bertin mentions recording, communicating, and processing.

Regarding form, the first thing to be noticed is the fact that, whereas text fundamentally is organized in *time*, the structuring feature of the graphical medium is *space* (see also Bertin 1983). The resemblance relation in combination with spatiality makes the graphical medium most appropriate for depicting spatial relations (see Fig. 7.1). The topology of objects in a scene, their positions and orientations from left to right and from top to bottom, is more easily inferred from a graphical representation because of the relatively straightforward mapping of the representation to the represented world (Larkin and Simon 1987). This type of semiotic relation corresponds to one of Peirce's categories, the "icon", the two other ones being "index" and "symbol". Note how the icon versus symbol distinction as an opposition of relations ruled by resemblance versus convention often gets blurred. For example, algebraic equations, as text, are organized in time (Bertin 1983) and so are said to be ruled by convention. However, one can just as well reason from their *structural* (rather than visual spatial) resemblance relations to what they represent. As another example, some pictures, such as ideograms, may be called icons and symbols at the same time. For instance, the drawing of a heart could stand for a human heart, in which case it would be an icon, or stand for love, in which case it would be a symbol. Visual material in multimedia research typically relies on resemblance relations, cf. a drawing of a bicycle pump, a schema of a car engine, or a diagram of the formation of a thunderstorm. These multimedia studies therefore seem to discard alternative meaning making processes within the visual medium.

Bertin analyses how the spatiality of the plane, i.e. the flat surface in printed matter, in terms of the visual variables can be exploited for information visualization. The information is most often arranged in a table (see Fig. 7.6). The properties of the plane are that it has two dimensions, height and width, on which one can establish one of three elements: a point, a line or an area. Therefore, one may use the size and the position of an element in the two-dimensional plane, and furthermore exploit the shape, orientation, color, texture and value for distinguishing between components. On the basis of form, Bertin distinguishes diagrams, maps, networks, and symbols.

- *Diagrams*. The graphic is a diagram "when the correspondences on the plane can be established between all the divisions of one component and all the divisions of another component" (Bertin 1983, p. 50). In Bertin's terminology, a component can be understood as a variable. Therefore, the first group includes line graphs, bar charts, histograms, and scatter plots.
- *Networks*. "When the correspondences on the plane can be established among all the divisions of the same component, the construction is a network" (Bertin 1983, p. 50). The second group includes all kinds of graphs, node-and-link diagrams, oriented graphs and charts of inclusive relationships.
- *Maps*. "When the correspondences on the plane can be established: among all the divisions of the same component and arranged according to a geographic order, the network traces out a geographic map" (Bertin 1983, p. 51).
- *Symbols*. "When the correspondence is not established on the plane, but between a single element of the plane and the reader, the correspondence is exterior to the graphic." (Bertin 1983, p. 51).

Bertin calls the latter category symbols because they appeal to some correspondence relation, i.e. an established convention, *outside* the graphic. The other three could be called icons for reasons of structural similarity. We could well say that this is a valid and appropriate, but to some researchers in the multimedia field, a counter intuitive interpretation of Peirce's triplet.

7.3.2 Classifying According to Domain Content

A fairly obvious way of classifying visualizations in teaching is to look at the domain content that is represented. The graphics used in different subject matters represent content of different nature and for a large part are derived from the expert practice within those disciplines.

- *Geography*. Textbooks in geography contain maps as spatial representations of data that have a spatial organisation. Cartography, the art of designing maps, is one of the oldest techniques of visualization and many techniques in the modern field of information visualization have their roots in cartography.
- *Physics and chemistry*. External representation takes up an important place in scientific practice (cf. Lynch and Woolgar 1990). When used in science teaching, Disessa (2004) calls them "cautioned" representations to refer to the history of many graphical formats, such as electrical circuit diagrams, spectra, diagrams of forces, molecular structure diagrams, etc. Researchers like Airey (2009) even stress the fact that representations, together with activities and tools, make up the disciplinary discourse that needs to be acquired by students at university level. Representations in physics can a have a more concrete as well as a very abstract nature.
- *Mathematics*. Representations are extremely present in mathematics because, as Duval (1995) mentions, the abstract objects of mathematics can solely be apprehended through different external representations.

We could extend the list of disciplines, the examples are numerous: Tukey box plots in statistics, ultrasonography in medicine, technical drawings and CAD models in engineering, and Venn and Euler diagrams in logics. Having to learn the particular representational formats of a discipline is in contradiction with the immediacy idea of graphics. Particular graphical conventions have to be acquired simultaneously with the domain concepts. The main difficulty in recognizing this insight is the fact that once the convention is learned, we no longer can distinguish it from our intuitions about a graphic. For example, the main intuition is that diagrams preserve topological information, but topological information has to be ignored when interpreting an electrical circuit diagram. Once we have learned the format, we seem to naturally disregard the topology of voltage or current sources, and of resistors, capacitors, inductors, and the like. Finally, there have also been other efforts to classify graphics according to the type of content. An example is the "periodic table of visualization methods" (Lengler and Eppler 2007) which distinguishes between visualization methods such as flowcharts for processes and concept maps for conceptual content.

7.3.3 Classifying According to Pedagogical Function

Both Carney and Levin (2002) and Levin (1979) developed a taxonomy for the function of pictures in pedagogical material in their view. Pictures are based on visual resemblance, i.e. they preserve the form of objects and the topological relations between objects in a scene. According to Carney and Levin (2002), pictures instigate student learning of unfamiliar content through the familiarity of their format. They also mention how pictures may complete text. The five categories specify the function of a picture either in teaching or with respect to its relation to the text.

- *Decoration*. The function of decorational pictures is to embellish pages. The aesthetics of pedagogical material is not only advantageous from a commercial point of view. In teaching, pictures are thought to attract attention and to motivate. An example of a decorational picture would be a drawing of a pine tree with a text about a hiking trail.
- *Representation*. Pictures are said to serve a representational function when they stand for some or all of the content presented in the text. This is the most frequently used function of pictures in pedagogical material. A picture of the heart, coronary arteries and cardiac veins in a chapter about the circulation of blood would be a clear example of the representational function.
- *Organization*. Organizational pictures, such as a step by step guide of performing cardiopulmonary resuscitation, provide structure for the content presented in the text.
- *Interpretation*. Interpretational pictures aim at clarifying difficult text, e.g., representing blood pressure in terms of a pump system.
- *Transformation*. The last function refers to transformational pictures. These pictures include systematic mnemonic components that are designed to improve a reader's recall of text information.

Schwartz and Danielson (2012) pointed out that Carney and Levin's five functions do not cover all functions of graphics and the majority of the graphics serve more than one function i.e. a graphic can be organizational and decorational at the same time. Roth, Pozzer-Ardenghi, and Young Han (2005) also presented a taxonomy comprising four functions of graphics: decorative, illustrative, exploratory and complementary. Finally, Marsh and White (2003) proposed a very detailed taxonomy with 49 functions that graphics can serve in relation to text. There are 11 major functions: decorative, elicit emotions, control, reiterate, organize, relate, condense, explain, interpret, develop and transform.

7.3.4 Contexts and Crossovers

The three ways of classifying graphics according to form, content, and function, seem to be relatively straightforward. However, no one would argue that their categories are exhaustive and mutually exclusive. Whenever inspecting authentic real world examples, as we will be doing below, one realizes the inherent awkwardness of these classifications. The context of a particular graphic, and the prior knowledge of the interpreter, cannot be abstracted away. For example, how to classify a poster of the London Underground on the wall of an English as a foreign language class?

7.4 Prevalence of Graphics in Textbooks

As a first step, we attempt a systematic categorization of the graphics in some French and Pakistani Geography and Physics schoolbooks. Table 7.1 shows a summary of category definitions taken from dictionaries, encyclopedias and books about information visualization.

These definitions occupy different positions on a resemblance – convention dimension. For example, when the resemblance relation concerns spatiality, it often does not need explication, i.e. for maps, the projection of spatiality to spatiality is in the definition and is intuitive. However, when the resemblance relation concerns proportionality, such as relative lengths of the bars in a bar graph to relative values of a variable, it needs to be explicit in both the definition and in a legend. It contains a conventional component.

All graphics in four text books of geography and physics from France and Pakistan were categorized (see Table 7.2). Table 7.2 clearly shows differences regarding the presence of graphical representations in these French and Pakistani textbooks. First of all, French textbooks (both geography and physics) contain many more graphics than Pakistani. In addition, graphical representations in French textbooks entail color, whereas Pakistani textbooks mostly contain black and white graphical representations. Finally, French textbooks comprise a larger variety of graphical representations than Pakistani textbooks. Table is the only type of graphical representation which exists in all four textbooks. These differences can largely be traced back to the differences in the available financial and technological means reserved for schoolbooks in both countries. When financial and technological resources are scarce, the type of graphical representations is reduced to the indispensable for particular domain contents. As can be read off from the table, the Geography content domain minimally requires maps and tables and for the Physics content domain, diagrams, line graphs and tables are essential. The low number of graphics in Pakistani textbooks is not likely to originate from national government policies. In Pakistan, the National Bureau of Curriculum and Textbooks (NBCT), also known as the curriculum wing, formulates rules and regulations regarding textbooks. The National Textbook and Learning Materials Policy and Plan of Action (Govt. of Pakistan 2007) does not pay any specific attention to visual or graphical material (see also Khalid 2010).

7.5 Exploring Teachers' Thoughts

The current study aims at an inventory of existing knowledge on visualisation types through an exploration of teacher conceptions on the pedagogical use of visualisations. There were three main objectives of this study. The first interrogation concerns teachers' awareness of different types of visualizations. If graphics are conceptualized as the tools of the pedagogical trade, then teachers should have a

Table 7.1 Summary of the category definitions

Label	Definition	Source
Map	"A graphic is geographic "map" when the elements of a geographic component are arranged on a plane in the manner of their observed geographic order on the surface of the earth"	Bertin (1983), p. 285
Diagram	"A simplified drawing showing the appearance, structure, or workings of something; a schematic representation"	Oxford online dictionary
Schema	"Showing the main form and features of something, usually in the form of a drawing, which helps people to understand it"	Cambridge dictionary online
Line graph	"Line graphs compare two variables. Each variable is plotted along an axis. A line graph has a vertical axis and a horizontal axis. A line graph is often used to visualize a trend in data over intervals of time – a time series – thus the line is often drawn chronologically"	MSTE Carolyn's Unit on Graphing
Illustration	"Any type of picture or decoration used in conjunction with a text to embellish its appearance or to clarify its meaning"	Columbia Electronic Encyclopedia
Pie chart	"A circle which is divided from its center into several parts to show how a total amount is divided up"	Cambridge dictionary online
Flow chart	"It's a type of diagram that represents an algorithm or process, showing the steps as boxes of various kinds, and their order by connecting these with arrows. This diagrammatic representation can give a step-by-step solution to a given problem"	Wikipedia encyclopaedia
Pictogram	"Pictogram is a visual presentation of data using icons, pictures, symbols, etc., in place of or in addition to common graph elements (bars, lines, points etc.)"	Businessdictionary.com
Bar graph	"A chart with rectangular bars with lengths proportional to the values that they represent. The bars can be plotted vertically or horizontally"	Wikipedia encyclopaedia
Table	"An arrangement of facts and numbers in rows or blocks"	Cambridge dictionary online
Hierarchy graph	"A system in which people or things are arranged according to their importance"	Cambridge dictionary online
Image	"A representation of the external form of a person or thing in art"	Oxford dictionary online

relatively homogeneous way of designating graphics. Our second aim is to see whether teacher impressions are domain-dependent. In domains with different uses of graphics, such as geography and physics, do teachers have different notions about authentic graphics? And third, we aim to explore the degree to which teacher

Table 7.2 Frequency of different types of graphics in four different schoolbooks (Anwar 2009; Jalta et al. 2004 ; Khattak & Khattak 2009; Parisi 2002)

	France		Pakistan		
	Geography	Physics	Geography	Physics	Total
Diagram	1	250	0	281	532
Image	206	123	0	23	352
Line graph	7	226	0	37	270
Map	159	3	66	0	228
Table	47	67	84	27	225
Schema	25	45	0	11	81
Bar chart	16	3	12	0	31
Pie chart	10	3	8	0	21
Pictogram	1	1	0	0	2
Flow chart	1	0	0	0	1
Total	473	721	170	379	1,743
No. of pages	281	335	240	358	1,214
No. of graphics/page	1.7	2.1	0.7	1.1	1.4

impressions might be culture-dependent. The underlying idea is that in countries with varying degrees of technological development, this would emerge from teachers' ideas about graphics.

The study involved an inventory of teacher conceptions through a detailed, semi open-ended interview. Such interviews allow the researcher to get insight information (Patton 2005) and provide an opportunity to the participants to discuss their interpretations of different concepts. The target population consisted of in-service higher secondary school teachers of physics and geography from France and Pakistan irrespective of age, gender, qualification and residential background. Snowball sampling (Patton 2005) method was applied for the sample because of the difficulties to gain access to teachers in both countries. Five French and five Pakistani secondary school teachers in geography and physics were interviewed in their home country.

A closed quantitative interview (Cohen et al. 2000) was used as research tool. The interview consisted of seven questions for each of eight different visualisations chosen from geography and physics text books from Pakistan and France. The questions concerned teacher impressions about categorizing graphics, the function of graphics in teaching, and student's comprehension. The interviews were conducted in schools or in the homes of the teachers according to their preference. The sessions ranged from 40 to 90 min. The interviews were recorded with formal permission of the teachers. All interviews were transcribed for analysis. The transcripts were scored with the help of an analysis grid. An open coding method was adapted to identify teachers' answers on categorizing graphics, functions of graphics and on teachers' assumptions on student comprehension. Each statement in the transcripts was read in the light of this analysis grid.

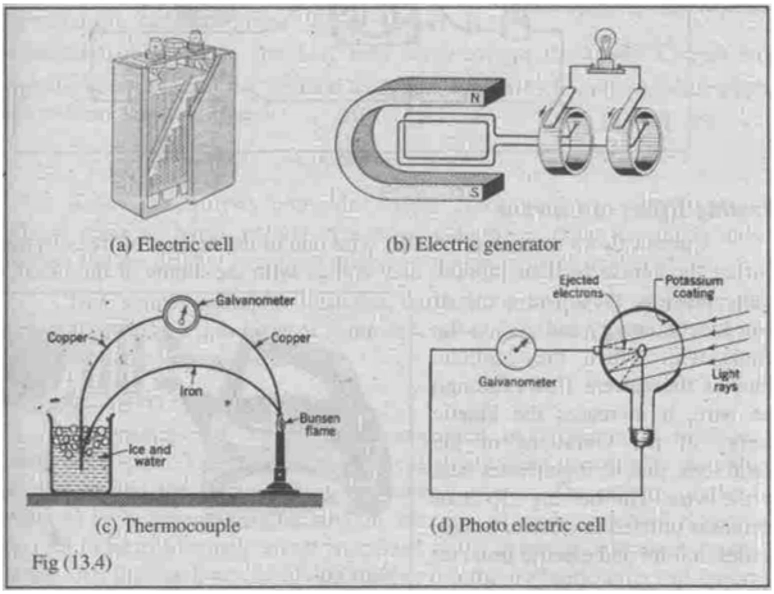


Fig. 7.2 A depiction in a Pakistani physics text book (Khattak and Khattak 2009, p. 53)

7.5.1 Teacher's Labelling of Graphics

All eight visualisations received more than one category name within the set of nine teachers. One teacher gave idiosyncratic responses and was left out. The most used categories labels were "diagram", "table", "map" and "line graph".

Most teachers thought of the first graphic (Fig. 7.1) as a map. Some specified that it could be considered a *planisphere* (world map in French). Thus, the peculiar circles and arrows on the map did not prevent most teachers from calling it a map. Two teachers distinguished themselves from this general tendency, one Pakistani Physics teacher called it an illustration and one Pakistani Geography teacher called it a graphic.

Most teachers thought of the second graphic (Fig. 7.2) as either a diagram or a schema, and less frequently as a figure or simply a graphic. In fact, the graphic contains resemblance-based graphics and abstraction-based graphics. Therefore, very general labels seem to be appropriate for the teachers.

The third graphic (Fig. 7.3) can be considered to be a hybrid between a map and a bar chart or histogram. This mixture was also evident in the teachers' responses. Most teachers simply thought of it as a map, but other labels, such as bar diagram or histogram, were also used.

Four teachers labelled the fourth graphic (Fig. 7.4) a diagram, but other labels, such as model, sketch, and even map, were also used. In effect, the graphic relies on resemblance, i.e. in the drawing of a tree, but also contains more abstract drawings and equations.

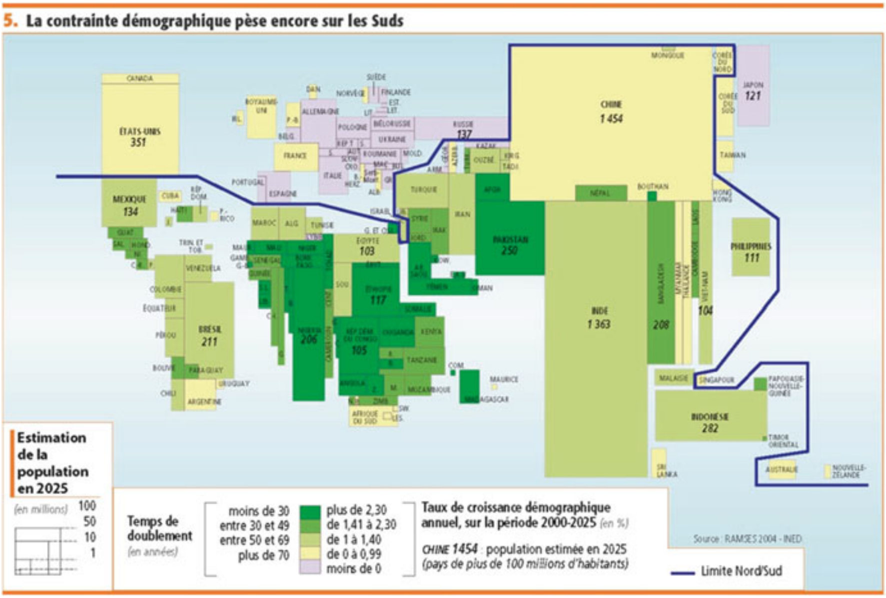
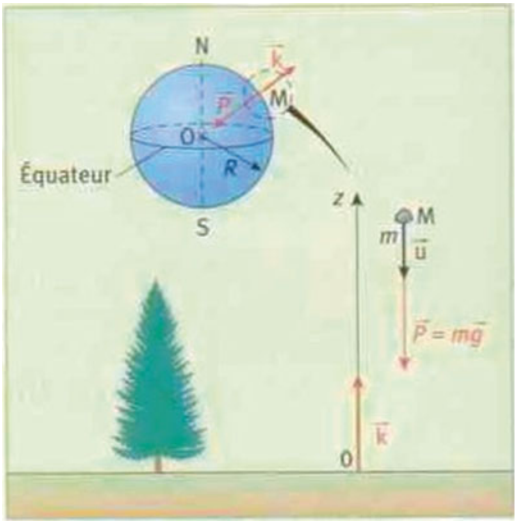


Fig. 7.3 A hybrid of a map and a histogram in a French geography textbook (Jalta et al. 2004, p. 55. © Editions Magnard)

Fig. 7.4 A graphic in the physics domain in a French physics textbook (Parisi 2002, p. 150)



This fifth graphic (Fig. 7.5) can be considered to be a bar chart with pictogram, or symbols according to Bertin's definition. Teachers did not use the labels pictogram or symbol, or even icon to refer to this graphic. Very general terms were used, such as figure, visual, image, and the like. Note that, whereas the graphic was taken from a textbook, it was originally not designed for instructional material.

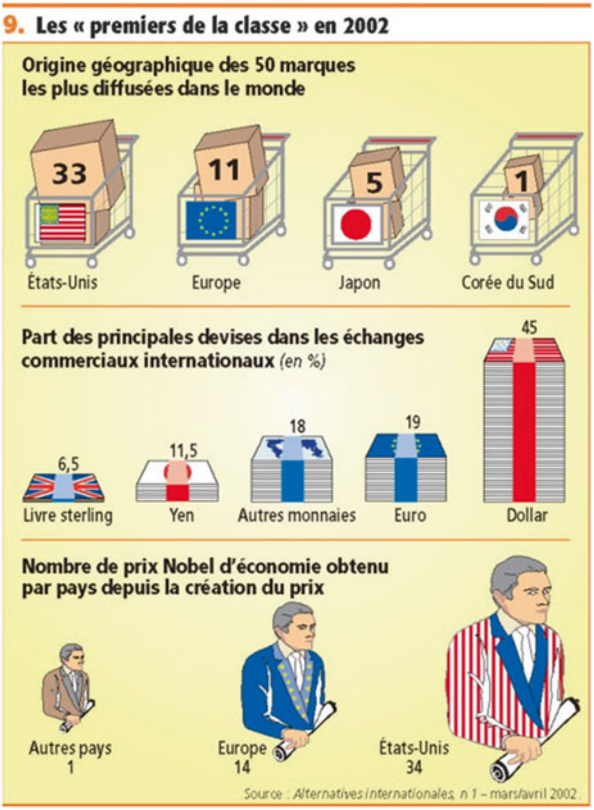


Fig. 7.5 A diagram in a French geography textbook (Jalta et al. 2004, p. 123. © Editions Magnard)

Fig. 7.6 A table in a Pakistani physics textbook (Khattak and Khattak 2009, p. 194)

Material	*Young's modulus Y (Pa)*	*Bulk modulus B (Pa)*	*Shear modulus S (Pa)*
Aluminium	7.0×10^{10}	7.5×10^{10}	2.5×10^{10}
Brass	9.0×10^{10}	6.0×10^{10}	3.5×10^{10}
Copper	11×10^{10}	14×10^{10}	4.4×10^{10}
Crown glass	6.0×10^{10}	5.0×10^{10}	2.5×10^{10}
Iron	21×10^{10}	16×10^{10}	7.7×10^{10}
lead	1.6×10^{10}	4.1×10^{10}	0.6×10^{10}
Nickel	21×10^{10}	17×10^{10}	7.8×10^{10}
Steel	20×10^{10}	16×10^{10}	7.5×10^{10}

The sixth graphic (Fig. 7.6) was identified as a table by all but one Pakistani physics teacher who labelled it a model.

Several labels were used for the seventh graphic (Fig. 7.7) but all can be assimilated to a line graph (curve graphic, graph). One French physics teacher called it a scatter plot.

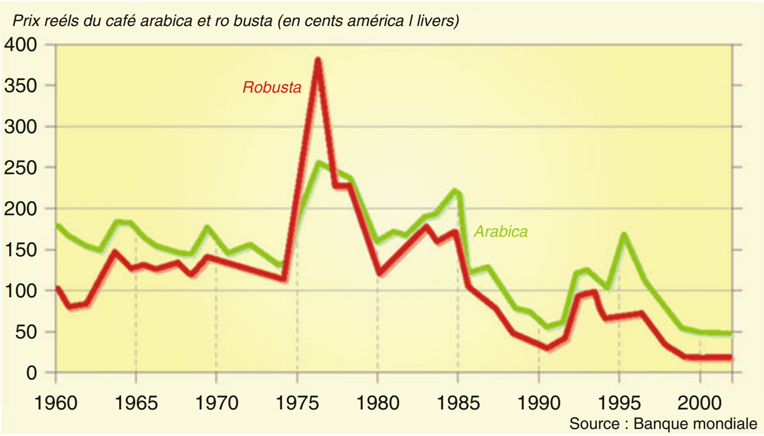


Fig. 7.7 A line graph in a French geography textbook (Jalta et al. 2004, p. 55. © Editions Magnard)

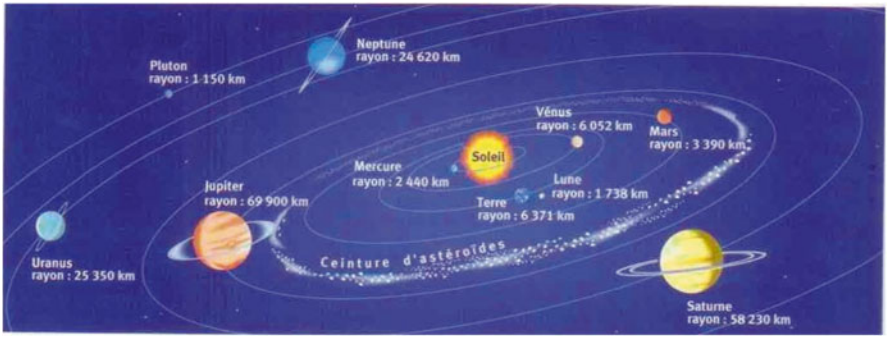


Fig. 7.8 A hybrid of a decorational and a representational function in a French physics textbook (Parisi 2002, p. 184)

The eight graphic (Fig. 7.8) was labelled a map, a diagram or a graphic.

The results of teachers' labelling of the graphics are summarized in Table 7.3. From this table, as well as from the foregoing, we observe several things. First of all, although some categories seem to be more clearly established, such as "map", "line graph", and "table", there seems to be no rigorous vocabulary to designate different types of graphics, at least not in the set of teachers we interviewed. Furthermore, there is no clear distinction between what might be called resemblance based graphics (figure, image, visual, sketch) and convention based graphics (line graph, diagram, table). Although we would like to think of the set of different graphical formats as an educational toolbox, no shared glossary can be identified. Teachers, as experts in the transmission of knowledge, do not seem to think of graphics in a systematic way that goes beyond the general public. Let us exploit the analogy: what to think about a craftsman who does not have names for the different tools of the crafts? If these results are considered generalizable, then we must come to the

Table 7.3 Teachers' labeling of educational graphics

	Graphic								
Given labels	1	2	3	4	5	6	7	8	Total
Map	6		5	1	1			2	15
Diagram		5		4	2			3	14
Table						8			8
Line graph							6		6
Schema		2							2
Illustration	1								1
"Planisphere"	1								1
Figure		1			1				2
Histogram			1						1
Hologram			1						1
Bar diagram			1						1
Image					1				1
Visual					1				1
Organigramme					1				1
Model				1		1			2
Scatterplot							1		1
Sketch				1				1	2
Graphic	1	1	1	1			1	2	7
Other				1	2		1	1	5

realization that visualisations, at least as they appear in today's textbooks in Western and non-Western societies, cannot be considered an integral part of a teacher's toolbox.

7.5.2 The Function of Graphics

From Carney and Levin's five pedagogical functions, the decorational function was largely discarded for the eight graphics by teachers from both countries and both content areas. Teachers did not think of any of the graphics as being functional in motivating or attracting students. The most important function of graphics, as indicated by teachers, is to present specific information on a topic and furthermore, for students to be able to study subject matter. These two combined correspond to Carney and Levin's representational function of graphics. In addition, the line graph in Fig. 7.7 was also thought to serve a comparison function between text and graphics.

Whereas Pakistani teachers seem to encourage memorizing data presented in tables for future recall, French teachers initiate exercises using tables so students will interact with the data. Moreover, Pakistani teachers adhere to traditional lectures with few opportunities for student participation. French teachers try to engage students in collaborative activities for understanding graphical representations.

Finally, Pakistani teachers stay closely to text books provided by the government. Teachers in France, on the other hand, exploit multiple resources, such as the internet, multiple textbooks and journals in order to vary graphical representations. Some French teachers also develop their own graphical representations.

7.5.3 Confidence in Student Comprehension

Teachers from both countries and both content areas expect that students will easily understand the eight selected graphical representations. The teachers' rationale for their anticipation of student understanding lies in the knowledge that students have encountered graphical representations of the same genre. Several teachers indicated that these kinds of graphics are routinely used in teaching. They mentioned that students, as they habitually study such graphical representations, are used to them.

Some of the teachers were somewhat less confident about student comprehension of the map-histogram hybrid displayed in Fig. 7.3. They think the graphic will be difficult for students to understand because "it is complicated" and "needs to be explained by the teacher". In looking for explanations, we might attribute this to the fact that the graphic is a hybrid of a map and a histogram. More precisely, it mixes two different resemblance relations, a spatial-geographical one of the topology of the countries on the surface of the earth and a logical-statistical one of the correspondence relation between the surface of the rectangles and the magnitude of the displayed variable.

7.6 Conclusions

Let us briefly relate back to the three viewpoints evoked in the introduction. Regarding the first one, the presumed visual turn, it led us to compare two countries that show different economic circumstances and technological development for graphics in textbooks. We question presumed relations between culture and education on the one hand, and teachers' thoughts about graphics in teaching and learning on the other hand. The economic circumstances explain differences in the presence of graphics in textbooks. Far more graphics are present in textbooks in France than in Pakistan. However, it is interesting to note that, in spite of tremendous differences in educational system, teacher training, pedagogy and textbooks, teachers exhibit quite similar thoughts regarding the use of graphics in teaching and learning. Abundance in graphics in Western textbooks does not, for the moment, lead to the emergence of a systematic approach to the transmission of knowledge using the visual medium. We found no hints to the presence of more sophisticated conceptions about the role of graphics, such as those described by Ainsworth (2006), or by diSessa (2004), or even relations between graphical formats and functional taxonomies. The notion of a semiotic educational toolbox remains illusory.

The second viewpoint concerned the fact that, although the visual spatial medium is often equated with resemblance relations, both similarity and convention may rule visualisations. Looking at genuine authentic graphics in textbooks from different countries and in different content domains makes one realise that graphics do still seem to be one opaque category. Very many different graphical genres co-exist, as well as very many different labels, but no unique mapping between genres and labels. The question arises as to the importance of the words used to label a particular type of graphical representation in relation to particular suggested interpretation strategies, i.e. a picture for superficial examination, a schema for analyzing, a cross-table for structuring. The association between a goal or need, and a tool for satisfying that need, is crucial in many expert domains. Craftsmen for example interact using a number of different designations to refer to different tools of their trade. From a set of similar looking tools, they recognize pliers, pincers, snips, shears and wrenches and may be asked to explicit what they are used for. Further research would be needed to explore educational graphics and visualizations as a conceptual field with a variety of goals, needs, tools, and interpretative activities. This is also important given the fact that technological means have considerably enlarged the spectrum of visualisation possibilities. The design of visualisations for learning therefore involves finding the balance between full exploitation of new visualisation techniques and the anticipation of their pedagogical appropriateness.

Finally, the third viewpoint involved the need or, on the contrary, the superfluity of graphical competency, graphical literacy or graphicacy. The assumption that information is readily available from graphics by virtue of immediacy was firmly anchored in teachers' thoughts. Across countries and domains, sheer exposure to graphics in the past, habitually encountering graphical material in textbooks, is allegedly sufficient for understanding even complicated graphics. Future research should inquire into the veracity and the nature of teachers' and learners' representational knowledge in general and for pedagogical purposes. Furthermore, future work should tackle the question of teaching of representational knowledge in teacher training and in school curricula.

Textbooks

Anwar, M. M. (2009). *Geography of the world for class XII*. Lahore: White Rose Publishers.

Jalta, J., Joly, J.-F., & Reineri, R. (Eds.). (2004). *L'espace Mondial Géographie Te S*. Paris: Magnard.

Khattak, M. A., & Khattak, A. A. (2009). *Physics for class XII*. Peshawar: Spinzer Enterprises Ltd.

Parisi, J.-M. (Ed.). (2002). *Physique term S*. Paris: Belin.

References

Agency for International Development (Dept. of State), Washington, DC. (2006). *Situation analysis of teacher education in Pakistan: Towards a strategic framework for teacher education and professional development*. Washington, DC: US Agency for International Development. Information Center, Ronald Reagan Building.

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction, 16*(3), 183–198.

Airey, J. (2009). *Science, language, and literacy: Case studies of learning in Swedish university physics.* Doctoral dissertation, Uppsala University

Bertin, J. (1983). *Semiology of graphics: diagrams, networks, maps*. Madison: University of Wisconsin Press (Translation by W. J. Berg of "Sémiologie Graphique. Les Diagrammes, les Réseaux, les Cartes" (1967)).

Bertin, J., & Berg, W. J. (2011). *Semiology of graphics: Diagrams, networks, maps*. Redlands: ESRI Press.

Carney, R. N., & Levin, J. R. (2002). Pictorial illustrations still improve students' learning from text. *Educational Psychology Review, 14*(1), 5–26.

Cohen, L., Manion, L., & Morrison, K. (2000). *Research methods in education*. London/New York:Routledge.

Coleman, J. (2010). Elementary teachers' instructional practices involving graphical representations. *Journal of Visual Literacy, 29*, 198–222.

Coleman, J. M., McTigue, E. M., & Smolkin, L. B. (2011). Elementary teachers' use of graphical representations in science teaching. *Journal of Science Teacher Education, 22*(7), 613–643.

Cros, F., & Obin, J.-P. (2003). *Attracting, developing and retaining effective teachers, country background report for France*. Paris: Organisation for Economic Cooperation and Development.

De Vries, E. & Lowe, R. (2010). *Graphicacy: What does the learner bring to a graphic?* Paper presented at the EARLI SIG2 meeting, Tübingen, August 2010.

Directorate General for Schools. (2010). *School education in France*. Paris: MEN.

diSessa, A. A. (2004). Metarepresentation: Native competence and targets for instruction. *Cognition and Instruction, 22*(3), 293–331.

Duval, R. (1995). *Sémiosis et pensée humaine: registres sémiotiques et apprentissages intellectuels*. Berne: Peter Lang.

Eco, U. (1976). *A theory of semiotics*. Bloomington: Indiana University Press.

Goodman, N. (1976). *Languages of art. An approach to a theory of symbols* (2nd ed.). Indianapolis: Hackett.

Government of Pakistan. (2007). *National textbook and learning materials policy and plan of action*. Islamabad: Curriculum Wing, Ministry of Education.

Lapostolle, G., & Chevaillier, T. (2011). Teacher training in France in the early 2010s. *Journal of Education for Teaching: International Research and Pedagogy, 37*(4), 451–459.

Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science: A Multidisciplinary Journal, 11*(1), 65–100.

Lengler, R. & Eppler, M. (2007). *Towards a periodic table of visualization methods for management*. IASTED Proceedings of the Conference on Graphics and Visualization in Engineering (GVE 2007), Clearwater, Florida. http://www.visual-literacy.org/periodic_table/periodic_table.html. Retrieved 31 May 2013.

Levin, J. R. (1979). *On functions of pictures in prose*. Madison: Wisconsin Research and Development Center for Individualized Schooling, The University of Wisconsin.

Lynch, M., & Woolgar, S. (Eds.). (1990). *Representation in scientific practice*. Cambridge, MA: MIT Press.

Lynd, D. (2007). *The education system in Pakistan: Assessment of the national education census*. UNESCO, Islamabad.

Khalid, M. (2010). Textbook evaluation in Pakistan: Issue of conformity to the national curriculum guidelines. *Bulletin of Education and Research, 32*, 15–36.

Marsh, E. E., & White, M. D. (2003). A taxonomy of relationships between images and text. *Journal of Documentation, 59*(6), 647–672.

Mitchell, W. J. T. (1994). *Picture theory. Essays on verbal and visual representation*. Chicago/London: The University of Chicago Press.

OECD, PISA 2009 Database. http://dx.doi.org/10.1787/888932343342. Retrieved 31 May 2013.

Palmer, S. E. (1978). Fundamental aspects of cognitive representation. In E. Rosch & B. B. Lloyd (Eds.), *Cognition and categorization* (pp. 259–203). Hillsdale: Lawrence Erlbaum.

Patton, M. Q. (2005). *Qualitative research*. New York: Wiley.

Rastier, F. (2000). On signs and texts: Cognitive science and interpretation. In P. Perron (Ed.), *Semiotics as a bridge between the humanities and the sciences* (p. 409). New York/Toronto: Legas Press.

Roth, W.-M., Pozzer-Ardenghi, L., & Young, H. J. (2005). *Critical graphicacy: Understanding visual representation practices in school science*. Dordrecht: Springer.

Sarwar, M., & Hussain, S. (2010). Teacher training in Pakistan: Problems and solutions for student teaching preparatory programs. *European Journal of Scientific Research, 46*(2), 179–185.

Schnotz, W. (2002). Commentary: Towards an integrated view of learning from text and visual displays. *Educational Psychology Review, 14*(1), 101–120.

Schwartz, N. H. & Danielson R. W. (2012). *What kind of graphic is this? A framework for delineating the graphics in text-graphic research*. SIG 2 Learning with text and graphics, European Association for Research on Learning and Instruction, Grenoble.

Tufte, E. R. (2001). *The visual display of quantitative information*. Cheshire: Graphics Press.

Wittgenstein, L. (1993). *Tractatus logico-philosophicus* (G. G. Granger, Trans. 1922 ed.). Paris: Gallimard.

World Bank. (2010). http://data.worldbank.org/indicator/SE.XPD.TOTL.GD.ZS. Accessed 14 Feb 2013.

Chapter 8
The Implications of Culture for Teachers' Use of Representations

Bruce Waldrip, Franco Rodie, and Sutopo Sutopo

Abstract This chapter explores how teachers utilize representations in their teaching. It illustrates this use through examples drawn largely from three regions of the world – Australia, Indonesia and Melanesia. They describes the value that these teachers perceived in utilizing these and how their use impacted on teaching and learning strategies. It explains representational attempts by teachers to enable student learning as they work with students to negotiate effectively between everyday discourse, culture, and values and those of the science community and to sustain connections between students community beliefs and canonical science in these settings. Some of the issues explored include the impact of status and gender, ownership and relationships, uniqueness of teaching approaches, societal and life experiences, need to link to student lives, impact of expert and student-generated representations on teaching and learning. It concludes through a discussion on how these representations are constrained by the assessment process and how they can be utilized to explore the development of understanding in each of these regions.

Keywords Australia • Indonesia • Melanesia • Teachers • Visual representations • Teaching • Culture • Beliefs • Learning • Pedagogies • Gender • Ownership • Teaching approaches • Social expectations • Assessment

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8.1 Introduction

In many non-western countries, learning can be viewed by what it empowers a person to do. The learner often sees a different agenda based on perceptions of the outcomes.

Karsoon *I like Melanesian ways. I wanted to learn Western ways and so when mission came, I went to school [so that I could] learn their ways. I thought I would learn new ways. I use school ways no more.*

Lapua *The white man didn't want us to learn about his ways but only about his religion. (*Waldrip and Taylor 1999b*, p. 297)*

Falgout and Levin (1992) argue that, for students in developing countries, the importance of knowledge lies in its application, results and products whereas Western schools view learning of knowledge for the sake of knowledge as a virtue. Okebukola (Okebukola 1986; Jegede and Okebukola 1991) argues that the learner's cultural background can impact more on learning than does the subject content. Differing worldviews can influence how teachers adopt teaching strategies and how students learn. Culture is more than an idea "to think with" (Eisenhardt 2001, p. 16). It influences how "people act and make sense of their world" (Eisenhardt 2001, p. 20) and includes discourses, group processes, "funds of knowledge" (Moll et al. 1993) and collective representations.

While there are problems in generalizing across cultures, in this paper, we will argue that there is a range of culturally related issues that need to be considered when using representations in different cultures. This chapter will illustrate relevant points based on data from Australia, Melanesia (area in western part of South Pacific Ocean), and Indonesia. In Melanesia, there are over 2,000 dialects that are spoken, ranging in area from a few villages to quite a substantial area, all located on over 1,000 islands. Some of these languages are matrilineal dominated while most are patrilineal resulting in quite different customs and learning expectations. Each language can have its unique cultural mores and values. Indonesia has many more islands than Melanesia and has a wide language diversity of about 700 languages. Javanese is the dominant language group within the country. However, Indonesian language (*Bahasa Indonesia*) is given preference over local dialects and becomes more dominant as schooling progresses. It is expected that the Indonesian language is the main medium of instruction from grade 4. These differences can influence how learning occurs in the classroom in both Melanesia and Indonesia.

8.1.1 Status and Gender Issues

Based on personal experience of all the authors, respect for societal positioning is very important. The status of children's families as well as their gender can influence how students perceive the quality of teaching and how they respond in class. Male teachers are afforded more respect and are more likely to be seen as authoritarian and expert. Upper male students are more likely to challenge a female teacher.

These perceptions can influence how the teacher presents learning material, particularly how they use representations. In addition, students from lower societal levels can have an expectation that these students will achieve less than students from chief or leadership families (Waldrip and Taylor 1999a) A similar view has been reported amongst Native American students (Swisher 1991). The lower societal students want to avoid appearing superior so that they don't clash with traditional cultural norms. They usually will not challenge an expert-developed representation (e.g. chart) that a male teacher shows the class even if that teacher makes an incorrect statement about the chart. If a female teacher constructs a representation, they can be challenged by a number of male students but this is less likely to occur if the teacher uses an expert-produced artifact for explaining the same concept. In this case, any challenge on the female teacher will tend to focus on how it is used or what explanations made rather than on the artifact itself. In addition, female students often refuse to participate in reporting learning outcomes until the males have finished and they tend to refuse to compete with male students (Baker 1998). This is important for achieving harmony within the society. Their own people will criticise them if they break these norms. Carlone and Johnson (2012) suggest this reflects the students' desire not to draw attention to themselves (other than recognized leaders) and to work for the benefit of the group. It is very important that the teacher learns to exploit these norms and values in ways that assist the student in developing and expressing their understandings. Bruce found it beneficial that students were given opportunities to share their understandings and experiences in carefully selected small groups. Later in this chapter, more specific examples will be discussed.

8.1.2 Ownership and Relationships

In some cultures, possessions are shared e.g. Melanesian and Native American cultures (Pewewardy 2008). In Melanesia, there is an expectation that possessions be shared within a "tok place", which loosely means a common language grouping. This means that it is important that ownership of a representation is shared unless a societal leader has developed it. It can mean that school property can be reallocated so that some students can have access to the possession of a representation within their place of accommodation (dormitory, house) rather than within the school classrooms. This view suggests that student-generated representations could result in greater student ownership in the learning process. The degree of shared ownership between school and students can impact on the teacher's relationship with the students. Usually, each student or small student group need to have access to the representation so they can make some claim about the representation. In both Melanesia and Indonesia, relationships are valued highly unlike Western society where possessions and achievements are more highly prized. Hence, it is important for opportunities for students to develop ownership of the representation used or generated.

The local students already have a culture and so the teacher, unless they are from that local culture, need to establish why they have something to contribute. The teachers should share some aspects about themselves so that the local students feel that trust and a working relationship are being established, usually through a dialogue (Kelly-Jackson and Jackson 2011; Morrison et al. 2008; Santoro et al. 2011). Consequently, the use of representations should involve teacher-students and students-students in a three-way dialogue (Roberts 1996) in establishing what the representation shows and how it contributes to understanding. Within many indigenous societies that use English as one language of instruction, a local form of English has emerged that is somewhat different to standardized English. Both Melanesia and Indonesia have a form of English that contains unique local characteristics. It is more important to focus on the concepts explained rather than address the correctness of the non-standardised English (Frigo 1999; Morrison et al. 2008), Students find it easier to verbalise rather than write their understandings. The use of representations in other modes can support this development of understanding (Jorgensen et al. 2009).

8.1.3 Teaching Approaches

Constructivist approaches to teaching can be problematic if the teacher doesn't immediately supply a response. While student discussion can be culturally appropriate, the teacher must consider carefully as to when and how they respond, even if they view student discussion of learning can lead to enhanced understanding. Including wait time and providing opportunities for discussion, can cause some students to question the teachers' ability to teach. This can be risky in some cultures as the lack of an immediate teacher answer can raise questions in some students' thinking as to the skills, knowledge and qualifications of the teacher because experts are expected to deliver immediate responses (Waldrip and Taylor 1999a). In Indonesia, the lack of an immediate teacher answer can raise student confusion as well. They expect the expert to readily supply a response or direction to student learning. Framing the interaction from a learning perspective as to how the local culture operates can reduce some of this perceived anxiety (Santoro et al. 2011; Waldrip et al. 2007). In addition, any discussion that utilizes the local language can aid in examining the key aspects of a representation as their understanding develops.

While working in Melanesia, Bruce was often surprised as to the detail of what students had observed. Being a Western person, he was accustomed to Westerners providing a summary of the main events of any observed incident. The local Melanesian students would describe, in detail and in order, what they had seen. They would rarely summarise the incident. There is a need for teachers to recognize that indigenous students will perceive different form and function of any representation and that the teachers needs to explore these views in a non-judgmental manner if students are to gain an understanding and to become engaged in the learning. In class, students would observe closely what Bruce was demonstrating and tried to replicate what they had seen. Traditionally, learning occurs through observations and then replicating what they have seen. Only once they become proficient and recognized as an expert, can they then develop the authority to introduce their own views. These students are quite visual and learn often through observation in a manner similar to traditional practices (Pewewardy 2008). We would suggest that developing physical representations, including models and role-plays, assists these students in developing their understandings.

8.1.4 Societal Expectations

In addition, there is a fear of not performing to the teacher's and other students' expectations. This fear can cause the student not to undertake a task or respond to a directive because they fear that they cannot replicate the standard expected of them. If students are asked to illustrate what their home (traditional) understanding of a concept is, then they can usually illustrate this knowledge. A similar situation applies in Indonesian schools. If students are asked to explain their observation or experience using their own language, they will do it immediately. However,, if asked to explain it scientifically, they usually search first for the relevant scientific term or similar explanation available in textbook. Because schools can appear to be intimidating and hostile to many indigenous learners, it is important for teachers to build a link between the school, students and families (Santoro et al. 2011). Hence, there is a need to make strong links between the canonical representation and their student generated representation to show a respect for their culture. Carolan et al. (2008) and, Prain and Waldrip (2006) suggest that multiple representations are an effective way to teach complex subjects as it facilitates multiple perspectives about the concept, often involving concrete approaches to the concept. In addition, this diverse range of representations can make learning more stimulating for students and encourage them to think and reason more deeply, facilitate connections between prior and new information and enables students to present and justify their understandings.

8.1.5 Life Experiences

Teachers and students in different cultures have had different life experiences. What one takes as normal might be new to someone else. In examining a teacher's use of representations, it is important to consider whether the representation is available to them or have they had previous exposure. Bruce can remember evaluating the effectiveness of the distribution of science resources across Melanesian schools. All schools had been supplied with identical sets of equipment with the aim of helping students' learning. For example, one of the items was a '3-D magnetic field demonstrator'. Bruce asked at a number of schools whether they had received it. In many cases they said no. In fact, it was found stored in each school's science storeroom. When teachers were asked to show how they used it, the most common response was to hold it up for people to see. They did not realize that it needed to be shaken first and for magnets to be inserted. This was a case that illustrates that all teachers might not know how to use the item. They had never heard of this item before, let alone been shown how to use it in teaching. In another case, one of the students helping in a teacher's home, knocked over a three-piece jigsaw. After some hours, they could not re-assemble the item. They had never experienced the art of assembling a basic jigsaw. However, they were able to find food and observe nature in a manner well beyond Bruce's capabilities. There are many ideas and content in science that these students have never experienced. For example, in everyday life, many Melanesians and Indonesians have not observed a traffic light or a 50-story office tower. It is very difficult for the teacher to explain these, even if they have seen them, to a student who has never seen them before. Analogies for these items can leave a lot to be desired. In the use of representations, if the teacher has had limited experience with the representation and what it depicts, the teacher might find it difficult to use, often resulting in literal interpretations of descriptions.

The solution is not always to show these people the real life objects as there might not be equivalent words or ideas in the local dialect. Similarly, the local senior science curriculum often has examples of industries and processes not found within the country. E.g. aluminium refining is a topic taught in Melanesia but no aluminium industry or related processes are found within the region. However, local processes can be used to explain some industries such as soap manufacturer. It is possible to use local ingredients (e.g. coconut oil, ash and salt water) to make soap and cover the basic steps. There is a need for some teachers to be skilled in curriculum areas if the curriculum is to remain the same and to develop other resources or modes that can address the underlying concepts. In both Indonesia and Melanesia, the availability of resources can be quite restrictive unless the school has comparatively well-resourced parents. In addition, many teachers are unaware of other resources that could assist in developing student understanding.

8.1.6 Linking to Student Lives

In a previous article, Waldrip et al. (2007, p. 112) illustrate the need for teachers to explain concepts and principles using stories and experience the students are familiar with before explaining the 'similarities and differences between their local understanding and what their books actually mean'. This idea links to the need for students to have an understanding in their own language, the ideas linked to their past experiences and then, as Roberts (1996) implies, a discussion on how it relates to the canonical understandings. Waldrip et al. also points out the need to link to community members as a resource in developing students' understandings (Frigo 1999; Jorgensen et al. 2009). In addition, visual imagery from students home can assist in making this link (Morrison et al. 2008). Morrison et al. points out the need to using student's strengths as a starting point of instruction. This can mean that there is a need for local stories or artifacts to be used as a representation, a focus on traditional explanations, a link to relevant science processes behind these observations.

8.1.7 Student Generated Representational Research

In this chapter, we accept that quality learning involves "active and increasingly competent participation in the representational or discursive practices of a classroom" (Prain and Tytler 2013, p. 7). We also accept that in quality learning, there is an interactive process between students' representations and those canonical representations utilized by the teacher.

The process of active construction of learning in the classroom contributes more to quality learning than does interpretation of canonical representations found in authoritative sources (e.g. textbook, web, videos, etc.) utilized by the teacher. As Tytler et al. (2013) point out, the act of constructing a representation focuses students' attention on the representation and can constrain students thinking to the essential aspects or key features of the representations (Bransford and Schwartz 1999). It provides students with a sense of agency in learning and an active opportunity to publicly display and justify their understandings. This view requires teachers to make judgments about the quality of student-developed representations and then facilitating the ongoing dialogue between students and also with their teacher about the robustness of any claim coming from the representation. It pressurizes the teacher to have an in-depth understanding of the content and an understanding of what is appropriate pedagogically for enhancing student understanding.

Recent researchers in science education argue that to learn science effectively, students need to understand the different representations of science concepts and processes, be able to translate a representation into one another, and understand their coordinated use in representing scientific knowledge (Hubber et al. 2010; Prain et al. 2009). The use of representations is to help students to grasp deeper understanding through integrating information from more than one representation.

The dominant research on representations is about the expert-developed representations. Such sanctioned representations are typically presented in textbooks or scientific publications, or provided by teachers in classroom. Representational skill is then defined as the ability to use, interpret, and construct such sanctioned representation (Ainsworth 2008; Kohl and Finkelstein 2005). The learning tasks are therefore focused on the use of representations individually or in coordinated ways to deeply understand a scientific idea or process, or on the construction of representations to solve a problem. There have been various researchers in this area. Some of them focus on the use of representations in problem solving including the effect of the format used in the problem to students' performance (e.g. Kohl and Finkelstein 2005, 2006b, 2008; Meltzer 2005; Nieminen et al. 2010; Rosengrant et al. 2009). The others focus on the effect of classroom atmosphere on students' representational skill (e.g. Kohl and Finkelstein 2006a; Kohl et al. 2007), or developing students' representational skill through specific treatment during a course (e.g. Ogilvie 2009; Podolefsky and Finkelstein 2006, 2007).

The emerging new area of research into representations investigates the value of student-generated representations to promote understanding in science (Waldrip et al. 2006, 2010). This is the approach adopted in this chapter. In this perspective, students learn to use material and symbolic tools to think scientifically, incorporating both new and old technologies (Carolan et al. 2006; Waldrip et al. 2006, 2008; Cox 1999; diSessa 2004; Greeno and Hall 1997; Saul 2004; Tytler et al. 2007; Prain and Waldrip 2006). We agree with Kozma and Russell (2005) that representations can function as conceptualizing and reasoning tools, rather than just as means for knowledge display. According to those studies, students' participation only in teacher-design activities may constrain opportunity for students' learning. It implies the need for learners to use their own representations. diSessa (2004) argued that students could productively design new representations, if given enough time and support, even approaching qualities of scientific representation: precision (clear or unambiguous), conciseness (give minimal but sufficient information), and completeness (comprehensive for its purpose). However, Carolan et al. (2008) reminded that students need guidance in making links between their own representations and authorized ones from the science community. Therefore, it is sensible to assume that a teaching approach that integrates reasoning and both sanctioned and student-generated representations may be able to promote students learning. In this respect, a representational approach to learning means students being able to state claims, reflect on what is appropriate evidence, as well as critique and modify the representation and then refine both initial reasoning and representation.

8.2 Context of Study

How teachers use these representations impact on how students develop their understandings. In the next section of this chapter we will note how or whether Australian, Melanesian, and Indonesian teachers' practices and beliefs influence their use of representations. In each sample, teachers were surveyed about their views, interviewed about their use and purpose of representations and at least one of the researchers observed their teaching. In addition, Bruce has taught in both Australia and Melanesian high school science classrooms.

The Australian sample includes an initial survey of 20 Australian teachers' practices and beliefs in using representations of science concepts for learning (Waldrip and Prain 2008) plus analysis of case studies based on classroom observations that did include some video-analysis. The Melanesian sample consisted of a survey of teachers in over 20 schools, participant observations of classrooms and personal experience of teaching in these classrooms. The Indonesian sample consisted of about 50 teachers and observations of high school science classrooms.

The Australian sample included both primary and high school teachers. All teachers had a 4-year teaching qualification. The students in these classrooms came from a wide range of socio-economic backgrounds.

In Melanesia, the range of teaching qualifications that can be found in schools range from a typical 4-year teacher qualification program to teachers employed who have only finished high school but have not received any form of teacher qualifications. The more qualified teachers tend to be found in the major centres. Schools located in major centres are considered more desirable for potential students as they perceive educational advantages if they attend a major centre school that can require them to live on campus. The more remote schools are also more restricted by availability of teaching resources and therefore perceived by some as less desirable. The teachers in this sample were perceived to be more highly capable Melanesian teachers located near to major centres.

It is reasonable to suggest that the Indonesian school system has strong centralist control from the bureaucracy. The schools have a range of availability of resources with some being well equipped, while others have limited availability of resources. The apparent availability of resources seem to be somewhat linked to the socio-economic status of the local community. That is, schools located in communities that have wealthier or more educated parents, tend to have better availability of resources. This increase in availability could be the result of teachers' creativity and parental expectations and support rather than increased funding provided by government. These schools tend to charge higher school levies or fees. In Indonesia, current typical teachers' qualification is Bachelor (4 years teacher preparation program) of Education degree. Most teachers in elementary school were high school graduates when they were first employed and obtained their bachelor's qualification through participation through in-service programs. Some teachers in the major centres will have obtained a master qualification, especially for work in more sought after middle or high schools. An Indonesian government target expects that all Indonesian teachers will have at least a Bachelor degree by the end of 2014.

The more remote schools are also more restricted by availability of teaching resources. The teachers in this sample were perceived to be more highly capable teachers. Some of them are pursuing a Master of Science Education. Some of them teach mathematics or science in schools that offer what Indonesia recognizes as an 'international standard curriculum' school (*SekolahBertaraf International* or National Plus School). At these National Plus schools, they are expected to teach science or mathematics in English, or at least, teach bilingually in Indonesian and English. Although English is a compulsory subject matter in middle and high school (grade 7–12), science and mathematics are taught in Indonesian but they are taught in English in National Plus schools. According to central Indonesian government policy, each district is expected to establish at least one National Plus school for every level of school (Elementary, Junior, and Senior school). There are about 490 districts in Indonesia.

8.3 Analysis

8.3.1 Teacher Status and the Expert

In certain cultures, the way the classroom is organized and the societal or customs are acknowledged can impact on how the teacher operates in that classroom. In Melanesian societies, discussion about certain science topics, e.g. reproduction in biology, is forbidden in mixed company. The way that teachers involve students in

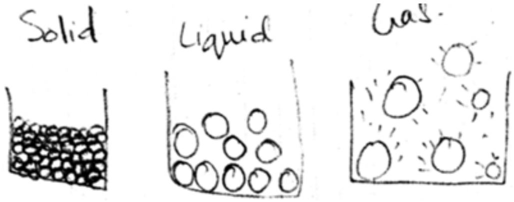

Fig. 8.1 States of matter replication of teacher's notes

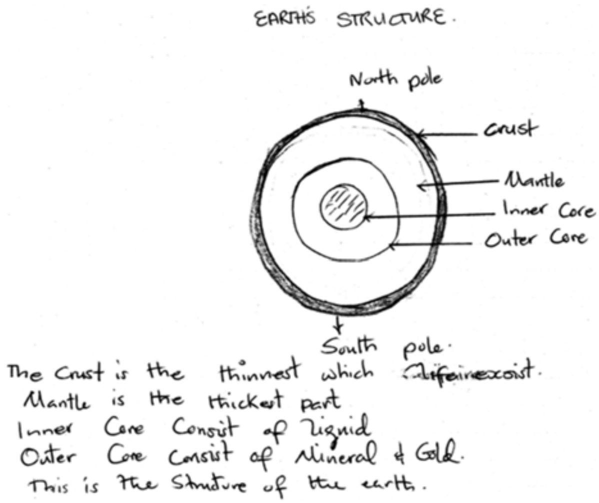

Fig. 8.2 Students' replication of textbook illustration of earth's structure

question generation is another factor. The teacher is seen as an authority figure and an expert. In Melanesia and Indonesia, the expert is not to be questioned. That is why he is an expert. As one Melanesian student put it:

> I asked my teacher a question. He said that is something for you to find out later. That raised a lot of questions in my mind whether he knew what the answer was and, if he did, he would have explained it to me and I would know. But if he doesn't know then if I have to ask the same question again, he probably say the same thing and there is no point of asking questions. I feel there is no point asking questions if he can't give me the answer. (Waldrip and Taylor 1999b)

This perspective can be reflected in students' views about the scope and purpose of textbooks and expert-developed audio-visual materials. Students often view them as authoritative even if they struggle to understand the content.

Hence, expert-derived materials can be perceived by students as being authoritative and sufficient to deliver understanding. This perception reinforces the perception that expert-generated representations are authoritative and not to be challenged. They are accepted as is. In addition, Melanesians report that they do not always know what are the critical features of an expert-designed representation. As a result, they memorize the whole artifact so that they can faithfully reproduce the artifact when needed. Both Melanesian and Indonesian teachers have a high degree of respect for the expert. Figures 8.1 and 8.2 illustrate these students' reproduction of

Fig. 8.3 Student exploring with heating of air particles in aluminum cans

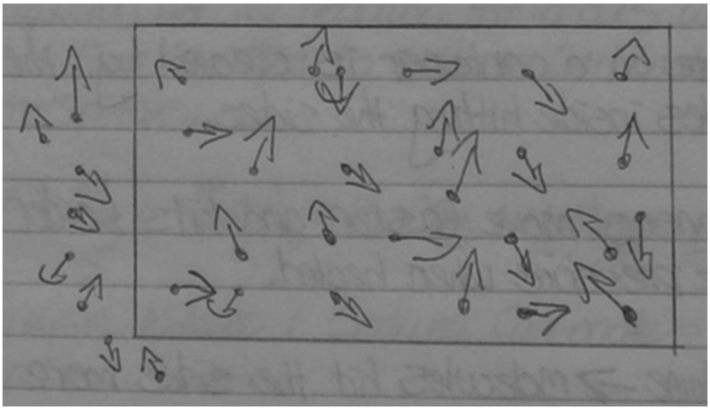

Fig. 8.4 Student representation of air particle distribution in heated can

expert-derived representations. They perceive if they can reproduce what an expert (teacher, textbook, scientist, etc.) has developed, then they understand the concepts.

While many Australian students also replicated textbook or teacher-developed representations, they were more likely to construct their own representations. For example, some students had explored what happens when an aluminium can is heated and it collapses when immersed in water as shown in Fig. 8.3. Figure 8.4 shows a student's representation of the distribution of air particles in a container before it was heated.

Indonesian parents usually educate their child to regard the teachers as representative of their parent in school. It is not acceptable for students to protest or confrontationally disagree with their teacher. Students are expected to obey to their teachers. As a result, students view their teacher as an expert that never does anything wrong.

Recently, because of the abundance of learning resources available in internet, and the children's ability to quickly learning to utilize internet, teachers have become more open to student accounts of concepts or questions. On the other hand, Indonesian teachers usually view university lecturers as well as educational supervisors as experts that they should defer to.

8.3.2 Extent of Use of Representations and Visual Resources

Our survey of Australian teachers tended to show that they

- tended to concentrate on the use of resources and students' learning styles rather than a diversity of representational modes.
- tended to think that consideration of learning style differences was important and that use of many different modes was better for developing student understanding.
- viewed a diversity of representational use was necessary for making topics and concepts more tangible, enabling students to "relate resources to their own lives".
- were aware of a range of possible representational modes.
- tended to use a diversity of resources to cater for perceived learning styles rather than as different representations of science methods and concepts.
- used a wide range of modes but did not focus on the specific interpretive demands of individual modes in planning, framing, and conducting diagnostic, formative, or summative assessment. (Waldrip and Prain 2013).

In summary, Melanesian teachers' use of representations can be affected by availability of representational resources but they

1. often improvise because of lack of availability of representational resources, hence utilize a narrower range of modes;
2. tended not to have access to multimedia resources;
3. believed that expert-derived representations could not be faulted; and
4. believed that a variety of resources allowed for differences in students' ability.

Analysis of survey, interviews and observations with Melanesian and Indonesian teachers show some similarity and indicated that more advanced technological resources, e.g., computer programs and videos, were not widely available. Generally, within Melanesia, few schools have access to computers, let alone access to the internet due to non-availability of internet connections by the relevant provider or lack of finances to fund the connection. However, many teachers did indicate their belief that internet and other multi-media would allow them to teach more effectively or that they would provide a resource for students to learn from. The teachers used a variety of resources that was dominated by the use of charts, posters, photos, diagrams, calculations, constructing tables of results and graphing data. They reported low use of computer programs, videos, animations, newspaper articles and cartoons. This lower level of use reflects lower levels of financial support. Cartoons are not widely available in local Melanesian newspapers. They did report that student drawings of what they saw or thought was happening was a relatively common feature in their teaching. This view could be a result of many students being asked to draw a canonical version of the observed activity. Some teachers did report that they felt that some visual representations allowed students to explain what they couldn't say in words.

The availability of different expert-produced representations (e.g. computer programs, videos, etc.) can mask the teachers' understanding of the concept in that the expert representation becomes a default position rather than a tool to assist in developing understanding. A number of these teachers use expert representations as another form of knowledge transmission and rarely address student views. In Melanesia and Indonesia, these expert representations are not always available. However, this lack caused some Melanesian teachers to improvise very effective representations from local materials. Hence, one needs to consider whether it is availability or teachers' understanding of the use of the representation that is the underlying factor.

Interestingly, Indonesian teachers reported that they introduced topics using stories to illustrate the concepts they were teaching. Like teachers in Melanesia, telling stories is an important teaching component in developing understanding. The ability of students to tell stories or use analogies in explaining their understanding was seen as indicating their initial understanding of a concept. Yet, in summative assessment, teachers reverted to the centralist view of mathematical manipulation or written expression to measure the extent of learning. Teachers viewed this storying or narrative recall as a means to stimulate student engagement, link to everyday life and to develop various perspectives about a topic.

In planning to teach a topic, Indonesian teachers perceived that expert or teacher designed materials e.g., computer programs, video, simulations, etc., was more effective in promoting learning. As a result, they were less likely to use a range of modes because that would interfere with time for students to solve problems, and the crowded curricula wouldn't allow for time to utilize a range of resources. A fairly common approach for teaching involved teachers introducing using a PowerPoint, picture or a narrative, an activity or a computer simulation to reinforce the concept and followed by students drawing what they had observed or performing calculations. Comparatively, few teachers reported that hands-on and experimental resources that engage students in active learning was important but they felt that computer programs and simulations were more efficient and likely to influence learning. Role-play or drama was almost never utilized to promote student understanding.

8.3.3 Impact on Teaching

The analysis of the Australian case studies revealed that the teachers recognized that this representational approach made new demands on their teaching skills and knowledge, including:

- their skill in teaching form/function relations of different representational modes;
- their ability to identify and make use of appropriate representational resources;

- the capacity to guide students from self-generated representations to authorised ones;
- their skill in moving students from dependence on concrete props to abstracting and symbolizing through representations;
- their skill in structuring social negotiation of different student claims and justifications.

In summary, Melanesian teachers use of representations can be affected by availability of representational resources but they

1. believed that use of representations were impacted by students ability with English language;
2. tended to ask students to reproduce rather than generate a representation;
3. felt that use of representations assisted students with lower literacy and language skills;
4. utilized more active hands-on or drama in teaching than Australian teachers;
5. felt that examinations can utilize expert developed representations but didn't support use of student-generated representations;
6. felt use of representations allowed a stronger link with the 'real world';
7. increasingly utilized representations in their teaching;
8. felt use of representations assisted in teaching and student engagement; and
9. reported that the use of representations provided a window into students thinking, thereby providing opportunities for productive diagnostic and formative assessment.

Both Melanesian and Indonesian teachers indicated that availability of resources could involve either a belief that they didn't have sufficient resources to teach and this lack does impact on their ability to use different representations to generate representations. While this can act as a blocker for most teachers, some Melanesian teachers viewed this lack of availability of resources as an opportunity to utilize or substitute local resources to develop student understanding. They reported that they had students gathering local materials, including plant and geological specimens, for construction of models of concepts, e.g. cell structure, chemical bonding, states of matter, etc.

The Melanesian teachers did indicate that teacher-produced diagrams and students writing or drawing about what they observed or did were a feature in their classrooms. Teachers generally have access to centrally written or purchased materials but often there is relatively little other material available for access. The focus on using texts or student copying material from the board can be viewed as a result of limited availability of alternatives. They emphasized that student familiar resources (e.g. utilised local materials as resources in developing student understanding such as using local fruits with sticks to construct molecules) are more preferable than expert developed resources e.g., textbook, teacher diagrams, charts. Interestingly, expert designed materials such as textbooks were seen to be a limiting factor in student learning. The use of these local resources is influenced by lack of availability of alternatives and the perceived benefit of these resources in improved student learning. A lower proportion of Melanesian teachers than the Australian teachers focused on how a variety of resources allow for differences in students' learning ability. However, student writing was a common feature in classrooms but this was a limiting feature due to variation in students' ability to write in English. In Melanesian schools, local dialect is used as the teaching medium in lower primary classrooms. The use of English as the medium of instruction is introduced in middle to upper primary school. By the commencement of high school studies, many students are still developing their mastery of written and spoken English. In Indonesia, as stated earlier, the teaching of Bahasa Indonesian became obligatory as schooling progressed. The Indonesian teachers didn't comment as to how a variety of resources allowed for differentiation in learning.

These Melanesian teachers thought that consideration of learning style differences was important while some teachers felt that use of many different modes was better for developing student understanding to a lessor extent than expressed by the Australian teachers. They viewed a diversity of representational use as necessary for making topics and concepts more tangible, enabling students to "relate resources to their own lives" while using a diversity of resources to cater for perceived learning styles rather than as different representations of science methods and concepts. As another teacher stated 'students differ from one another in terms of most effective because some they see things before they actually understand the concept. Others perhaps need different modes, e.g., something they hear, feel or smell to engage in a topic.'

The availability of different expert-produced representations (e.g. computer programs, videos, etc.) can mask the teachers' understanding of the concept in that the expert representation becomes a default position rather than a tool to assist in developing understanding. A number of these teachers use expert representations as another form of knowledge transmission and rarely address student views. In Melanesia and Indonesia, these expert representations are not always available. However, this lack caused some teachers to improvise very effective representations from local materials. Hence, one needs to consider whether it is availability or teachers' understanding of the use of the representation that is the underlying factor.

8.3.4 Impact on Learning

For the Australian teachers, the representational approach was perceived to benefit teaching and learning in that it:

- Improved student knowledge building
- resulted in improved student engagement and achievement;
- provided a window into students thinking, thereby providing opportunities for productive diagnostic and formative assessment;
- provided a meaningful learning experience through potential linkage with everyday experiences.

For these teachers, their beliefs about, and practices in using representations impacted on how they taught and assessed.

Reflecting back on their teaching career, Melanesian teachers reported increased use and variety of representations during their years of teaching experience as they felt that their use improved student learning. Many teachers felt that re-representations of their understandings allow students to 'present ideas in a way they understand it or show an understanding that might be more difficult to reveal in another form and it can shows '*how I can assess that there has been learning*.' While teaching, they viewed students' comments as evidence that they are listening and reference is made by them as to how any comments are linked to the matter under consideration but no teacher mentioned how the comments could be linked to developing an enhanced understanding or used as a reasoning tool to improve understanding.

Similar to the Australian teachers, both Indonesian and Melanesian teachers stated that the representational approach was perceived to benefit teaching and learning in that it improved student knowledge building processes but there was less evidence that this was implemented in practice. Some Melanesian teachers felt that their use would result in improved student engagement and achievement as students could display in a way that allows them to show what they think, especially those students who had difficulty in expressing themselves in written English.

When Indonesian teachers were asked as to what modes assist student learning, Indonesian teachers expressed the view that models, computer simulations and videos were more likely to result in improved student learning. This view seems to reflect an opinion and observed practice that expert-developed material was more appropriate to stimulate student learning. However, this could be a reflection on the availability of resources and what the teachers were familiar with rather than what actually improved learning. Indonesian teachers expressed a smaller range of modes than did the other teachers, again indicating a reflection of the availability of resources or the centrally available curriculum resources. They tended to see different resources as a way of providing an authoritative resource to back their explanations and would address a deficient learning situation.

8.3.5 Assessment of Acquired Knowledge

In the Australian sample, there was limited use of representations in formal assessment. When students were asked to produce a visual representation, they tended to reproduce their understanding of expert designed representations. There were relatively few opportunities for students to provide their own views. As a number of students stated, they felt that teachers weren't interested in drawing or other representations unless it was asked for. In stead, they felt that teachers wanted to see what one wrote in a test.

Melanesian teachers were divided as to whether students constructing pictorial displays of understanding be used in examinations. Australian, Melanesian and

Indonesian teachers comments largely indicated that these students were expected to re-construct canonical representations. Teachers viewed that these range of resources supported or complemented each other in developing students' understanding of concepts. One teacher stated '*some students are better with interpreting pictures or diagrams but others with visual, preferring models'*. They believed that use of selected resources provided an economic approach to learning in that they presented a concept in a way that saved time for the teacher. In addition, the emphasis on examinations pressures teachers to adopt teacher centred approaches that they view as more economical in preparing students for external examinations (Morrison et al. 2008).

The Australian sample was collected in Queensland that does not have an external examination system. Melanesian and Indonesian teachers reported a restricted range of assessment methods as they viewed assessment as being driven by the central examination process. They used tests as the main form of assessment with limited use of different resources in diagnosing and monitoring of learning. However, some teachers reported the use of a range of resources in monitoring learning, e.g., role-play, diagrams. They did view that students should be able to label diagrams in examinations but few indicated that there was a need in formal examinations to allow students to construct their own representation. One teacher, while not exactly arguing for inclusion of student-generated representations in examinations, stated that 'some students cannot explain well but do use their visual ability to aid explanations' in examination settings. This view was reflected in their construction of local tests.

Indonesian teachers reported that they monitored learning through questioning students and checking whether their responses matched expectations and used a teacher generated quiz to measure understanding. Examinations form a dominant component of the Indonesian education system. Like the Melanesian teachers, testing tended to be summative, externally driven and mainly written with little opportunity for them to construct their own views.

8.3.6 Formative Assessment

All teachers reported that the use of representations provided a window into students' thinking, thereby providing opportunities for productive diagnostic and formative assessment but relatively few teachers implemented this. It was clear that some teachers endeavour to use representations as a means to monitor learning resulting in their view that it provided a meaningful learning experience through potential linkage with everyday experiences. Even though one teacher stated that '*student drawing reveals to the teacher how much they understand from what they have observed'* the underlying position is mainly teacher-directed and -initiated. In our experience with Australian teachers, once teachers start implementing a representational approach to reasoning, they increasingly use representations as a form of monitoring learning. They see it as a tool for reasoning that results in increased

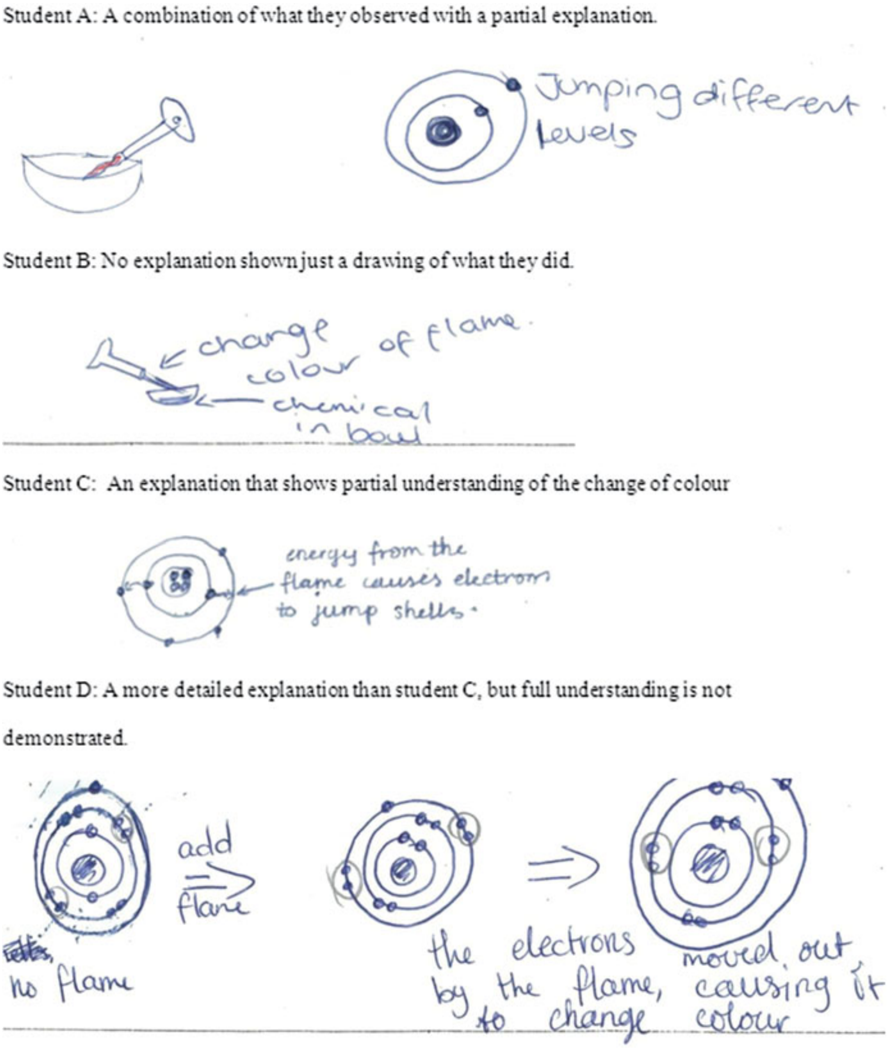

Fig. 8.5 Illustrative range of student generated representations as formative feedback in an Australian classroom

student engagement and student perception that it increases individualization of their learning. Initially, there is some resistance to this approach but this soon becomes a feature of learning within the classroom and students strongly indicate that they don't want to return to previous approaches to teaching and learning. When teachers explore students' understandings and reasons through a student-generated approach to learning, a range of understanding provides supportive feedback to the teacher about students' understanding of the concepts. Figure 8.5 shows a range of student understandings that can inform the teacher as to what needs to be addressed and how effective was the instruction in developing understanding.

Task: After performing a flame test practical exercise, students were asked to "Draw a picture to show WHY the flame changed colour". Some of the responses included:

8.3.7 Student Activities Including Experiments

All teachers felt that hand-on and experimental resources that engage students in active learning was important and that a range of approaches were useful in assisting learning to a higher extent than did the Australian teachers. The Melanesian utilized role-play to a greater extent than Australian teachers. For example, they taught the difference between parallel and series circuits using role-plays. One teacher referred to the need to link representations when they said that they needed to utilise diagrams, experimental activities and role-plays in teaching electrical circuits. Another stated that student drawing reveals to the teacher how much they understand from what they have observed.

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Overall, teachers tend to look for students' ability to create a representation that reflects the expert view, e.g. graph, model, drawing, etc. When teachers were asked to what extent they required students to represent an idea in different forms, they reported that they thought it was valuable for students to report in a variety of modes but it appears this variety was linked to resources available and the replication of expert-generated modes. This is further illustrated when they responded to a question about asking students to show their understanding pictorially. Almost every teacher referred to students re-constructing an expert version. In external examinations, a range of representations, that are usually expert-developed, is used in the format of problems and students are asked to respond these representations.

Reflecting on their teaching career, teachers reported that at first they focused on teaching the class and that as they gained experience and opportunities for increased availability of resources, they utilized more expert-developed resources in their teaching. They felt that it was important for students to be able to discuss their understandings with other students. The main outcome for using different forms of representations was that it promoted student creativity, deepened understanding, and reflected students' understanding of the topic. Even though it was not reported very much in other responses, teachers implied that student drawing did help them learn. However, observations indicate that teachers didn't often use them to allow students to show their initial, developing and resolved understanding of a topic.

8.3.8 Collaboration in Learning

There is a need for caution when studying different cultural groups in their use of representations. Different cultures can display different levels of openness. For example, Melanesians, who often view anything produced by an expert as authoritative, display this practice of showing their understanding quite openly, while as many Australian students will try and hide their level of understanding of expert-developed representations. In addition, group collaborative work involving reflective discussions, while culturally appropriate, is not a common feature in Melanesian classrooms. Traditionally, group work that create a sense of belonging like sharing events or discussions (Morrison et al. 2008) is a feature of their life but not well utilized in classrooms. In Australian classrooms, group work is quite common in primary classrooms and some secondary classrooms; it rarely develops to a level in which reasoning and justification becomes a tool to enhance understanding. Kelly-Jackson and Jackson (2011) point out that it is important that each student in a group has a particular task that requires cooperation of each member to achieve success.

The availability of different expert-produced representations (e.g. computer programs, videos, etc.) can mask the teachers' understanding of the concept in that the expert representation becomes a default position rather than a tool to assist in developing understanding. A number of these teachers use expert representations as another form of knowledge transmission and rarely address student views. In Melanesia and Indonesia, these expert representations are not always available. However, this lack caused some teachers to improvise very effective representations from local materials. Hence, one needs to consider whether it is availability or teachers' understanding of the use of the representation that is the underlying factor.

8.4 Conclusion and Implications

Teachers' choice of modes to develop understanding is impacted by the availability of resources. Both the Indonesian and the Melanesian teachers viewed expert-developed resources as important in developing understanding, but the Melanesian teachers did report the ability to develop modes from local materials. The Australian teachers did report a wider range of modes but this appears to be related more to their availability of knowledge of these resources rather than a pedagogical reason.

There is display of a great respect for experts and expert-designed representations by both students and teachers, hence, the use of representations in learning tends to be in the expert form where students are expected to reproduce the canonical forms and there appears to be relatively little critiquing of the representation and their mapping to key features and their limitations.

Once availability and knowledge about the use of resources was considered, there appears to be little difference in terms of culture as to how teachers used a range of representations. All teachers felt that there was scope for greater use of technology but this could be viewed that they perceived expert-developed resources as being more appropriate for learning. There is a need for students to realize that rather than accepting that an expert-developed representation is perfect, there is a need to examine the limitations and mapping between their own perceptions of the artifact and the concept or actuality. Culturally, the Indonesian and Melanesian teachers viewed the use of expert-developed modes as important in developing understanding. The Australian teachers were less likely to admit this but their emphasis on teacher-centred teaching reflected this view. There seemed to be little realization that cultural practices could be utilized in developing student understanding. There were few instances where teachers used folklore and practices to introduce the topic and student-student discussion involving justification and verification of their ideas that they then presented to the class as a process to develop common understandings. While teachers recognized that drawing could impact on student learning, it wasn't a strong feature of their planning and they seem yet to be convinced that it is important in developing student understanding in examinations or tests.

There are implications for all classrooms as to how learning science recognizes cultural differences and how these differences can be best utilised to facilitate learning. The concept as to what is expert knowledge in the eyes of the teacher compared to that of the learning of the student needs to be further explored in teacher practice. There could be a recognition that foreign aid, its form and nature, is usually dictated by the donor country that recognises the value of local expertise and relevant cultural learning approaches. Much international aid seems to assume a deficit model. That is, something is wrong with this country and we know the best way to fix this that doesn't recognize the local context. The resulting adoption of Western teaching approaches can be counter-productive to learning and, in some cases, conflict with local mores and values. A shift to a greater focus on student learning and reasoning would shift attention from what we have and what knowledge we have to how are the students learning, how do we know and how does this make sense to their own lives and culture.

References

Ainsworth, S. (2008). The educational value of multiple representations when learning complex scientific concepts. In J. K. Gilbert, M. Reiner, & M. Nakhlel (Eds.), *Visualization: Theory and practice in science education* (pp. 191–208). New York: Springer.

Baker, D.A. (1998). *A study of the effect of culture on the learning of science in non-western countries*. Unpublished Ph.D. thesis, Curtin University of Technology, Perth.

Bransford, J., & Schwartz, D. (1999). Rethinking transfer: A simple proposal with multiple implications. *Review of Research in Education, 24*, 61–100.

Carlone, H., & Johnson, A. (2012). Unpacking 'culture' in cultural studies of science education: Cultural difference versus cultural production. *Ethnography and Education, 7*(2), 151–173.

Carolan, J., Prain, V., & Waldrip, B. (2008). Using representation for teaching and learning in science. *Teaching Science, 54*(1), 18–23.

Cox, R. (1999). Representation construction, externalized cognition and individual differences. *Learning and Instruction, 9*, 343–363.

diSessa, A. A. (2004). Metarepresentation: Native competence and targets for instruction. *Cognition and Instruction, 22*(3), 293–331.

Eisenhardt, M. (2001). Educational ethnography past, present and future: Ideas to think with. *Educational Researcher, 30*(8), 16–27.

Falgout, S., & Levin, P. (1992). Introduction. *Anthropology and Education Quarterly, 23*, 3–9.

Frigo, T. (1999). *Resources and teaching strategies to support aboriginal children's numeracy learning. A review of literature*. Sydney: Office of the Board of Studies NSW.

Greeno, J. G., & Hall, R. P. (1997). Practicing representation: Learning with and about representational forms. *Phi Delta Kappan, 78*(5), 361–368.

Hubber, P., Tytler, R., & Haslam, F. (2010). Teaching and learning about force with a representational focus: Pedagogy and teacher change. *Research in Science Education, 40*(1), 5–28.

Jegede, O., & Okebukola, P. A. (1991). The relationship between African traditional cosmology and students' acquisition of a science process skill. *International Journal of Science Education, 13*, 37–47.

Jorgensen, R., Grootenboer, P., & Niesche, R. (2009). Insights into the beliefs and practices of teachers in a remote indigenous context. In R. Hunter, B. Bicknell, & T. Burgess (Eds.), *Crossing divides: Proceedings of the 32nd annual conference of the Mathematics Education Research Group of Australasia* (Vol. 1). Palmerston: MERGA.

Kelly-Jackson, C. P., & Jackson, T. O. (2011). Meeting their fullest potential: The beliefs and teaching of a culturally relevant science teacher. *Creative Education, 2*(4), 408–413.

Kohl, P. B., & Finkelstein, N. D. (2005). Student representational competence and self-assessment when solving physics problems. *Physics Review Special Topics – Physics Education Research, 1*, 010104.

Kohl, P. B., & Finkelstein, N. D. (2006a). Effect of instructional environment on physics students' representational skills. *Physics Review Special Topics – Physics Education Research, 2*, 010102.

Kohl, P. B., & Finkelstein, N. D. (2006b). Effect of representation on students solving physics problem: A fine-grained characterization. *Physics Review Special Topics – Physics Education Research, 2*, 010106.

Kohl, P. B., & Finkelstein, N. D. (2008). Patterns of multiple representation use by experts and novices during physics problem solving. *Physics Review Special Topics – Physics Education Research, 4*, 010111.

Kohl, P., Rosengrant, D., & Finkelstein, N. (2007). Strongly and weakly directed approaches to teaching multiple representation use in physics. *Physics Review Special Topics – Physics Education Research, 3*, 010108. Washington, DC.

Kozma, R., & Russell, J. (2005). Students becoming chemists: Developing representational competence. In J. Gilbert (Ed.), *Visualization in science education* (pp. 121–145). Dordrecht: Springer.

Meltzer, D. E. (2005). Relation between students' problem-solving performance and representational format. *American Journal of Physics, 73*(5), 463–478.

Moll, L., Tapia, J., & Whitmore, K. (1993). Living knowledge: The social distribution of cultural resources for thinking. In G. Salmon (Ed.), *Distributed cognitions* (pp. 139–163). Cambridge: Cambridge University Press.

Morrison, K. A., Robbins, H. H., & Rose, D. G. (2008). Operationalizing culturally relevant pedagogy: A synthesis of classroom-based research. *Equity & Excellence in Education, 41*(4), 433–452.

Nieminen, P., Savinainen, A., & Viiri, J. (2010). Force concept inventory-based multiple-choice test for investigating students' representational consistency. *Physics Review Special Topics – Physics Education Research, 6*, 020109.

Ogilvie, C. A. (2009). Changes in students' problem-solving strategies in a course that includes context-rich, multifaceted problem. *Physics Review Special Topics – Physics Education Research, 5*, 020102.

Okebukola, P. A. (1986). The influence of preferred learning styles on cooperative learning in science. *Science Education, 70*, 509–517.

Pewewardy, C. (2008). Learning styles of American Indian/Alaska native students. In J. Noel (Ed.), *Classic edition sources: Multicultural education* (pp. 116–121). New York: McGraw-Hill.

Podolefsky, N. S., & Finkelstein, N. D. (2006). Use of analogy in learning physics: The role of representation. *Physics Review Special Topics – Physics Education Research, 2*, 020101.

Podolefsky, N. S., & Finkelstein, N. D. (2007). Analogical scaffolding and the learning of abstract ideas in physics: Empirical study. *Physics Review Special Topics – Physics Education Research, 3*, 020104.

Prain, V., & Tytler, R. (2013). Representing and learning in science. In R. Tytler, V. Prain, P. Hubber, & B. Waldrip (Eds.), *Constructing representations to learn in science*. Rotterdam: Sense Publishers.

Prain, V., & Waldrip, B. G. (2006). An exploratory study of teachers' and students' use of multi-modal representations of concepts primary science. *International Journal of Science Education, 28*(15), 1843–1866.

Prain, V., Tytler, R., & Peterson, S. (2009). Multiple representation in learning about evaporation. *International Journal of Science Education, 31*(6), 787–808.

Roberts, D. (1996). Epistemic authority for teacher knowledge: The potential role of teacher communities: A response to Robert Orton. *Curriculum Inquiry, 26*(4), 417–431.

Rosengrant, D., Heuvelen, A. V., & Etkina, E. (2009). Do student use and understand free-body diagrams? *Physics Review Special Topics – Physics Education Research, 5*, 010108.

Santoro, N., Reid, J., Crawford, L., & Simpson, L. (2011). Teaching indigenous children: Listening to and learning from indigenous teachers. *Australian Journal of Education, 36*(10), article 5. http://ro.ecu.edu.au/ajte/vol36/iss10/5.

Saul, W. (Ed.). (2004). *Crossing borders in literacy and science instruction: Perspectives on theory and practice*. Newark: International Reading Association and National Science Teachers Association.

Swisher, K. (1991). *American Indian/Alaskan Native learning styles: Research and practice*. http://www.ericdigests.org/pre-9220/indian.htm. Accessed 30 July 2012.

Tytler, R., Prain, V., & Peterson, S. (2007). Representational issues in students learning about evaporation. *Research in Science Education, 37*(3), 313–331.

Waldrip, B. G., & Prain, V. (2008). An exploratory study of teachers' perspectives about using multi-modal representations of concepts to enhance science learning. *Canadian Journal of Science, Mathematics, and Technology Education, 8*(1), 5–24.

Waldrip, B. G., & Prain, V. (2013). Teachers' Initial response to a representational focus. In R. Tytler, V. Prain, P. Hubber, & B. Waldrip (Eds.), *Constructing representations to learn in science*. Rotterdam: Sense Publishers.

Waldrip, B. G., & Taylor, P. C. S. (1999a). Permeability of Students' world views to their school views. *Journal of Research in Science Teaching, 36*(3), 289–303.

Waldrip, B. G., & Taylor, P. C. S. (1999b). Standards for the cultural contextualisation of interpretative research: A Melanesian case. *International Journal of Science Education, 21*(3), 249–260.

Waldrip, B., Prain, V., & Carolan, J. (2006). Learning junior secondary science through multi-modal representation. *Electronic Journal of Science Education, 11*(1), 86–105.

Waldrip, B. G., Timothy, J. T., & Wilikai, W. (2007). Pedagogical principles in negotiating cultural conflict: A Melanesian example. *International Journal of Science Education, 29*(1), 101–122.

Waldrip, B. G., Prain, V., & Carolan, J. (2008, August 27–29). Using representations for teaching and learning in science. In A. Maes & S. Ainsworth (Eds.), *Proceedings EARLI special interest group text and graphics: Exploiting the opportunities – Learning with textual, graphical, and multimodal representations* (pp. 119–122, 152–156). Tilburg: Tilburg University.

Waldrip, B., Prain, V., & Carolan, J. (2010). Using multi-modal representations to improve learning in junior secondary science. *Research in Science Education, 40*, 65–80.

Chapter 9
The Interplay Between Language and Visualization: The Role of the Teacher

Liliana Mammino

Abstract Teaching and learning depend on communication. Language is the first and most fundamental communication tool and instrument of thought. Because of its conceptual components, science education requires adequate language-mastery sophistication.

Visualization is a very important communication tool, capable of: • providing complementary explanations reinforcing and clarifying those provided by the text; • focusing learners' attention on aspects and details that would otherwise remain unnoticed; • familiarising learners with entities that are not part of direct experience, like the invisible world of atoms and molecules in chemistry; • expressing trends through diagrams; • and conveying complex ensembles of operational information that would be too lengthy and less efficient to express through language, like the information on how to build something, typical of engineering projects.

Handling (reading, interpreting, drawing) images relevant to science learning and science communication requires specific training. The training is realised through language and, therefore, the development of visual literacy depends on language mastery and is unavoidably poorer when language mastery is poorer. Experience has shown that the interplay between language and visualization is an important key to pursue the maximum development of visual literacy attainable under given educational circumstances (i.e., considering the background preparation and communication abilities of a given group of students) and, at the same time, maximum clarification of the concepts concerned. This interplay can be managed only by the teacher and can become an important tool both for explanation and for in-class interactions.

The chapter analyses the main features of the interplay and outlines implementation pathways, illustrating them with a number of concrete examples. The analysis and the explored implementation options are the outcomes of direct experience in

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an underprivileged context where both the language mastery and the visual literacy of students entering university need substantial upgrading to become functional to learning. Information about the difficulties encountered by students in this context has been collected systematically in the last 15 years within the first year general chemistry course and the undergraduate and postgraduate physical chemistry courses, utilising both students' works and classroom interactions as sources. The information has been utilised to design implementation options, and students' responses have been utilised for subsequent re-optimisations of the options. Inferences are drawn from patterns in the documentation collected and in students' responses (including the general inference on the pedagogical importance of the interplay between language and visualization). It is further considered that educational approaches designed to promote underprivileged students can benefit all the other students, as they are designed with particular attention to ensure clarity and to avoid taking any prior knowledge for granted.

Keywords Visualization • Educational function of visualisation • South Africa • Language mastery • Communication • Teaching and learning • Chemistry • The interplay between language and visualization • Images captions • Misconceptions

9.1 Introduction

9.1.1 Language and Visualization as Communication Tools

Teaching and learning are communication-dependent processes, because they are realised through communication. Their effectiveness largely depends on the ways in which each of them is utilised and on the quality of the utilisation, i.e., on the clarity with which material is presented and on learners' abilities to understand communication through a given tool and to, in turn, utilise that tool to communicate.

Language and visualization are the most common communication tools used in science education. Language is the first and most fundamental communication instrument, being the fundamental instrument of thought, as we do not only express our thoughts through words and sentences, but also develop them (in our minds) through words and sentences. Language is capable of reaching high sophistication levels to express descriptions with any wealth of details, to express logical frameworks, and to express discourses with any degree of complexity. In the sciences, language is essential for all the description and inquiry aspects (describing systems and phenomena, identifying relationships between pieces of information, identifying investigation questions, formulating hypotheses and verifying them, making inferences) and in the trains of thoughts leading through interpretations to theories. Consequently, science education requires adequate language-mastery sophistication if learners are to reach satisfactory understanding levels (Mammino 2010a).

Visualization has acquired essential roles in science practice, such as:

- providing a complementary way of seeing mathematical relationships, through the mutual correspondence between geometry shapes and equations;
- conveying complex ensembles of operational information (complex sets of instructions) that would be too lengthy and less efficient to express through language, like the information on how to build something, typical of engineering;
- expressing and analysing logical frameworks (e.g., through flow charts);
- analysing information where shapes have fundamental roles (e.g., for the analysis of molecular geometries in computational chemistry);
- highlighting details (e.g., details of structures);
- expressing and highlighting trends in observed data (e.g., through diagrams).

These functions are integral components of science education, but visualization also plays other important roles in science teaching and learning. Its communication immediateness and its clarification abilities make it a powerful explanatory tool. The generation of mental images is fundamental for conceptual understanding (Harre 1970). On a brief overview, the educational functions of visualization include:

- providing complementary explanations reinforcing and clarifying those provided by words;
- attracting and focusing learners' attention on aspects and details that would otherwise remain neglected or be unnoticed;
- being a particularly useful tool for in-class interactions (Mammino 1999a);
- providing feedback on students' perceptions and mental images, and on the extent of their general understanding, which enables real-time interventions by the teacher.

The roles of language and those of visualization in science education have been objects of extensive attention in educational research. Even a minimally-representative review of existent literature would exceed the space available for a chapter. One may recall some classical works on the importance of language mastery, like those by Munby (1976), Carré (1981) or Wellington and Osborne (2001), and some more recent investigations, like that by Brooks (2006) on the role of language in physics learning. A number of studies have identified language-mastery inadequacies as the major cause of the difficulties that many students experience on reading and understanding science books (Davies and Greene 1984; Fang 2006) or on expressing ideas in their own words (Muralidhar 1991). The recommendation to utilise reading and writing (the tools of literacy "in its fundamental sense", Norris and Phillips 2003, 2008) in order to enhance science understanding constitutes a recognition of the primary role of language-mastery. The recommendation of "teaching science as a language" (Sutton 1992, 2003; Brown and Ryoo 2008) encourages the incorporation, into education, of part of the philosophical perspectives on the role of language in the discourse of science itself.

The importance of visualization in science learning is related to its ability to provide external representations that facilitate understanding (Gilbert 2008). Within chemistry-related contextual perspectives, its importance is highlighted in the many studies that have considered learners' understanding of the particulate nature of matter (e.g., Gabel, Samuel and Hunn (1987), Gabel (1993)), or those showing how learners' conceptions about the microscopic world can be aptly diagnosed through images (Smith and Metz 1996). The continuous increase of its importance both in science development and in science learning is further emphasised by conferences specifically devoted to it, like the biennial Gordon Research Conference on "Visualization in Science and in Education".

On the other hand, studies focusing specifically on the relationships and mutual interplay of language and visualization are still scarce. This chapter focuses on the language-visualization interplay (LVI) in science education, maintaining mostly practical perspectives based on direct experience.

9.1.2 Interplay Between Language and Visualization

As communication tools, language and visualization are not mutually independent. The extent and modes of their interplay vary largely for different domains and different activities. The interdependence may come close to zero for activities that focus dominantly on one of the two; for instance, we do not need to be able to use language at high sophistication level in order to enjoy a painting or another work of the visual-plastic arts; similarly, we do not need to visualize it, in order to enjoy reading a novel. In most science areas, LVI is extensive and inherent in the discourse. It brings mutual enhancement of the efficacy of each tool and simultaneously determines the need for adequate mastery of each of them. For instance, drawing a diagram requires understanding the relationships involved (which are expressed through words) and being able to represent them; conversely, interpreting a diagram requires being able to express through words (at least at mental level, in our thoughts) the kind of relationship that the diagram is meant to show. When diagrams are present, both the text and the diagram are integral components of the given discourse: inadequate understanding of one hampers the understanding of the other and, often, the understanding of the overall discourse. Similarly, a model of a molecule, resulting from calculations, prompts reflections and inferences which are expressed through language and which, in turn, may drive attention to other visualized aspects, so that LVI results in a sort of oscillatingly dominant utilisation of one or the other. Because of all this, the awareness of LVI and the generation of the ability to master it at reflection and communication levels need to be an integral component of science education.

Experience with science education highlights the interdependence of language and visualisation. When language-mastery and visual-literacy are both well developed, communication within teaching and learning activities can reach high levels of effectiveness and articulation. Poor language-mastery hampers the development of visual-literacy; it may hamper it up to the point of nearly disabling the communication function of visualization. Poor visual literacy decreases the communication effectiveness of visualization; it may decrease it up to the point that visualization does not bring any support to communication through words or even risks generating additional misconceptions. The combination of poor language mastery and poor visual literacy brings communication weakening or communication failure (Rubanza 2002), jeopardising the effectiveness of the teaching and learning activities. This is clearly evident in disadvantaged second-language contexts, like several contexts in Sub-Saharan Africa (Mammino 2010b). However, while research on the inherent disadvantages of second-language instruction is extensive (e.g., Rubanza 2002; Benson 2004; Alexander 2005; Brock-Utne and Hopson 2005; Brock-Utne and Skattum 2009; Heugh 2009; Mammino 2010b; Qorro 2011), research into how the difficulties inherent in second language instruction, or poor language mastery in general, affect the development of visual literacy (and, more specifically, of the type of visual literacy needed for science learning) is still scarce.

The influence of LVI on skills development can be tracked to its sources by considering the nature of the two communication tools and how literacy develops for each of them. Language literacy develops through talking (from the baby stage and onwards) and through a variety of other activities – reading, learning the theory of one's own language, learning other languages, learning any other subject in school syllabi at all levels, and any activity requiring thinking. Visual literacy develops through gradual familiarisation with the use of images. Its development requires language as a teacher-learner communication tool, to guide progressive familiarisation with the interpretation of images (identifying the correspondence between details of images and pieces of information that can be expressed through words, as well as learning how to represent known information through images). Thus, the acquisition of visual literacy depends on language mastery and is unavoidably poorer when language mastery is poor.

Handling (reading, interpreting and drawing) images relevant to science learning and science communication requires specific training. Students who have not been shown or taught how to read images fail to interpret even the simplest ones. LVI can be used as a major key to pursue the maximum development of visual literacy attainable under given educational circumstances (background preparation and communication abilities of a given group of students) and, at the same time, maximum clarification of the science concepts involved. This interplay can be managed only by the teacher and can become an important tool both for explanations and for in-class interactions.

The next sections analyse the main aspects of LVI and outline possible operational pathways, illustrating them with concrete examples from my direct experience.

9.2 Focusing on the Teacher's Role

The teaching and learning process is an interactive activity, and it is not easy to draw a crisp boundary between the teacher's side and the learner's side. In an ideal approach, the learner responds to the teacher and the teacher responds to the learner in a continuous interchange. Therefore, it is impossible to consider one side without simultaneously considering the other. On the other hand, the two roles are different and it is possible to try and focus mostly on the teacher's perspective, while still keeping in mind that it cannot be separated from the learner's perspective. This is the attempt that is carried out in this chapter.

9.2.1 Interplay Between Language and Visualization: Some Direct Experience

The experience-based information (or experimental evidence) used here refers to chemistry teaching. This, however, does not restrict the validity of findings and inferences solely to chemistry, because chemistry comprises most of the roles with which language and visualization are used throughout the sciences (Mammino 1999b). The major roles of visualization in chemistry teaching are the following (Mammino 1998a):

- the basic visualization inherent in structural formulas (which can actually be viewed as an overlap between symbolic representation and visualization);
- the illustration of details of accessible objects or procedures, to better attract students' attention to relevant aspects (e.g., illustrating the steps of an experiment);
- relating classroom information to everyday life;
- providing images of entities that are not accessible – the invisible entities of the microscopic world of atoms and molecules – to stimulate familiarisation through the generation of mental images of their structures and behaviours;
- representing phenomena and trends through diagrams;
- conveying design information through technical drawings (e.g., in chemical engineering).

The author has two major types of direct experience with the design and use of LVI:

- Twenty-seven years chemistry teaching in different contexts in Sub-Saharan Africa. This has highlighted the importance of LVI in the development of visual literacy (through the analysis of the impact of the reduced language mastery ensuing from second language instruction), and the need to design specific addressing options.
- Preparation of a chemistry textbook pursuing student-friendliness through the systematic use of imagery integrating the explanations of the text and being supported by careful guidance to its interpretation (Mammino 1994, 2003).

The major educational challenges are common to both experiences: how to design images that communicate rigorous scientific information despite the simplification often inherent in visualization, and how to ensure that learners get the desired messages from images. In both cases, the teacher needs to provide guidance to learners for them to learn how to read images. Although the implementation modes are different for the two objectives, the guidance relies on LVI for both cases. Meeting the same challenges from two different perspectives has had a crucial role in the design and development of the approaches that will be outlined in the rest of the chapter.

9.2.2 Teaching Learners How to Read Images – Guidance on Preparing a Textbook

Writing a textbook is an intensive "teaching action" differing from classroom teaching because it is meant for a larger audience (not limited to learners but extending to their teachers), and because it lacks direct interactions with that audience, thus lacking immediate feedback on the selected pedagogical options. On the other hand, information on possible learners' responses and perceptions is essential to the design of pedagogical options. This prompted a series of informal interactions with Italian secondary school pupils (aged 16–17 and at their first encounter with chemistry) to investigate their difficulties in reading chemistry textbooks, considering both the text and the imagery components of a book. The investigation was carried out (although not continuously) in the years 1984–2003 and showed that most pupils failed to grasp significant parts of the meaning of images, or even their entire meaning. Although it was clear that most of those pupils were not used to analysing the details of images and to relating each detail to a specific bit of information, it also became clear that several difficulties originated from the characteristics of the images themselves. No specific example is given here because it would entail the consideration and critical analysis of specific images from specific textbooks (what would be both too delicate and beyond the scope of this chapter). The following major inferences were derived:

- The need for images to be clear, highlighting one or two major points per image and carefully avoiding risks of misinterpretations. In other words, images need to respond to the language-of-science criteria of being rigorous, clear and simple (Mammino 1995), in full accordance with their communication-tool nature. It was concluded that, rather than overcrowding an image with excessive information, it is preferable to utilise sets of logically related images.
- The need for thorough guidance for the connections between text and images and for the reading of images. This relies on LVI.

The guidance to the connection of an image with the text is provided within the text, by highlighting the role of the given image when the reference to it is most fruitful. The guidance on reading images is realised through captions. Meticulous captions were designed to stimulate learners to consider all the informative details of individual images, or to move step-by-step through sets of related images meant to illustrate phenomena or behaviours (in the latter case, the guidance extends to the connections between the information provided by an image and that provided by the previous one). As an example of details to be highlighted, the caption of an image containing both representations of neutral atoms and representations of their positive ions will also attract the learner's attention to the different size of the spheres representing them (Mammino 1998b). Later-stage interactions with teachers confirmed that such detailed guidance was useful for learners and also for their teachers.

This experience set important foundations for in-class activities, both for the on-the-spot design of images responding to students' responses on a given issue/topic and for the design of guidance to images-interpretation. The same attention to details was systematically maintained in the class (e.g., always respecting size-proportions when drawing atoms and their ions on the board, and attracting students' attention to this). Moreover, the investigation of Italian pupils' difficulties with chemistry imagery provided interesting references to distinguish – at least at a first approximation – between difficulties that appear across contexts (and may be related to the conceptual demands of chemistry, or to the inadequacies of the modes of teaching it that we have so far been able to design) and difficulties that may be more closely related to the specificities of an underprivileged context, such as second-language instruction or poor skill-acquisition in pre-university instruction. This, in turn, enabled better targeting of different types of difficulties within in-class activities.

9.2.3 Teaching Learners How to Read Images – Guidance at Classroom Level

In the class, the guidance to images-reading relies mostly on interactions and entails careful analysis of the meaning of each detail of an image. LVI is maximised by systematic conversion of information through images into descriptions through sentences and vice versa. For instance, the familiarization with the informative roles of diagrams is stimulated by systematically providing the description of their physical meaning and inviting students to do the same. Effective focusing of this guidance relies on the teacher's familiarity with the types of difficulties encountered by students with specific types of diagrams. It will be discussed more in detail in a next section.

In-class interactions also entail students' active engagement in the design of images, so that visualization as a communication tool is not utilised only in one direction (from teacher to learner) but in both directions. Activities of this type rely extensively on LVI. Some options were outlined in a previous study (Mammino 2008), above all for the familiarization with the molecular level in first year general chemistry, and include activities like inviting students to draw molecular structures on the basis of solely-geometric information, or collaborative building of representations of the microscopic events during a chemical reaction (the gradual formation of products' molecules and the corresponding disappearance of reactants' molecules). This chapter focuses more specifically on LVI on designing explanation or remedial-intervention approaches, with particular attention to the role of the information made available by students' responses. The "responses" term is here used in its broadest meaning, incorporating everything that can be part of what the learner acquires (or does not acquire) after a certain explanation or other modes of introducing a topic; thus, it includes what he/she has understood or not understood, the perceptions or mental images he/she has developed, possible misconceptions he/she has developed, the interest he/she has developed; etc.

The information utilised in the next sections refers to chemistry teaching at the University of Venda (UNIVEN, South Africa) in the years 1997–2013, with the following courses involved: first year general chemistry, second year physical chemistry (chemical thermodynamics), third year physical chemistry (electrochemistry, chemical kinetics and surface chemistry), third year process technology (introduction to chemical engineering), first postgraduate physical chemistry course (quantum chemistry), second postgraduate physical chemistry course (spectroscopy, NMR and statistical thermodynamics). UNIVEN is a historically disadvantaged university located in a poor rural area in South Africa. Incoming students suffer from serious under-preparedness, in terms of serious insufficiencies in previously acquired information, poor mastery of the language that is the medium of instruction (English: a second/foreign language for them) and poor mastery of fundamental learning tools. Visual literacy is often very poor (Mammino 2008). The need to build literacy (both for language and for visualization) is a first priority (Mammino 2012).

The classroom activities for the previously-listed courses – and, therefore, also for all the examples considered here – entail the use of drawing in its basic meaning: drawing on a board or stimulating students to draw in their notebooks. This option was selected both because of technical reasons (non availability of other options that would enable individual students to make their own drawings) and on the basis of teacher-students agreement, because it is the option that enables maximum interaction and active engagement, as needed when developing basic literacy. The images reproduced here maintain the characteristics of how they are drawn by the teacher or by students, to reflect approaches and situations faithfully.

9.2.4 Images as Explanation, Diagnostic and Interaction Tools in the Class, and the Role of the Language-Visualization Interplay

Visualization can be an explanation tool, a diagnostic tool and a tool for classroom interactions, and can be relevant also for problem solving. All these roles rely on LVI.

A teacher needs a variety of diagnoses: learners' acquired ability to utilise a certain tool (to utilise language, to read and interpret images, or draw images to communicate information); learners' prior knowledge of a given topic (prior to introducing that topic) and learners' responses and acquired perceptions after the topic has been introduced. Experience from previous groups in the same context provides valuable indications. In-class short questions enable quick diagnoses and real-time decisions and interventions (Mammino 2013); utilising both questions requiring answers through sentences and questions requiring answers through imagery broadens the diagnostic spectrum.

Explanations may involve images at different stages and for various purposes. Experience and practice help identify the occasions on which it is more convenient to start from images and those on which it is more convenient to start from statements or descriptions. For instance, experience at UNIVEN has shown the presence of misconceptions related to non-rigorous definitions of direct and inverse proportionality provided at pre-university level. When the concepts need to be utilised (e.g. before introducing the ideal gas laws in the first year), students are asked to provide a definition. The typical answer is that two quantities, x and y, are directly proportional if y increases as x increases and inversely proportional if y decreases as x increases. Then the teacher draws several different graphs corresponding to “y increases as x increases” and asks students to identify the one representing direct proportionality. After the identification of the correct graph, students are invited to provide a correct definition of direct proportionality and, after it, to identify the relationships expressed by the other graphs. It could be said that, for misconceptions associated with prior provision of incorrect definitions, it is convenient to start from the definition that students know, use imagery to stimulate reflections on its faults, and guide those reflections towards the formulation of a correct definition. It is however not easy to identify a general-type rationale, because the value of an option depends of a number of individual-character factors, both in relation to the specific issue concerned and in relation to the learners’ background. Because of this, experience becomes the dominant criterion. If previous years experience shows that a certain combination of alternating and integrating focus-on-language and focus-on-images has greater impact on students (attracts their attention better and enables deeper acquisition and longer permanence of the new information), then that sequence can be considered viable until new experiences highlight the need for a different one.

Fostering the habit to use images as a way of expressing information has important impacts also on problem solving. Some problems require an initial drawing to identify the relevant information. A typical example is the calculation of the enthalpy of a certain bond knowing the enthalpies of the other bonds in a given molecule (second year physical chemistry course): students who do not draw the structural formula of the molecule being considered fail to solve the problem because they fail to identify how many bonds of each type are present in that molecule. Similarly, in the case of questions asking to write the Schrödinger equation for a given atom or molecule, students who do not draw a scheme (nucleus and electrons for an atom, nuclei and electrons for a molecule) fail to write the equation.

9.3 Some Excerpts from Classroom Experience

9.3.1 Methods and Approaches

This section considers a number of examples to illustrate both the benefits of LVI for explanation and clarification and the impact of students’ inadequate familiarity with it. The scenario at UNIVEN highlights the extreme consequences – on science learning – of inadequate language mastery and of its hampering impact on the acquisition of other skills, including visual literacy.

An extreme scenario requires extensive diagnostics to provide the pre-requisite information needed for the design of options aimed at addressing students’ difficulties in a way that can prompt desirable responses. This necessity has motivated a systematic collection of information – mostly from students’ routine works, like tests and laboratory reports, but also from in-class interactions – throughout the last 15 years. The outcome is a huge amount of documentation on answers, misconceptions, inadequate understanding, language-related problems, tendency to omit specific bits of information or to confuse specific items, difficulties at reading or drawing images (including diagrams), and various other learning problems. The analysis of this information aims at singling out the significant details of each type of difficulty, as valuable indications for the design of teaching options. Attempts to track possible causes rely on personal interviews.

Many details of explanations (in lectures, tutorials or laboratory-briefings) aim at attracting students' attention to those features for which the collected information shows inadequate understanding or even inadequate awareness (not noticing the presence of a given feature). Ideally, each error would require specific explanation in the class, and each deficiency (insufficient ability to do something) would require specific training. Under existing conditions (large enrolment groups, huge amount of aspects that would need clarifications or training, absence of teaching assistants), it becomes necessary to design approaches meant for entire groups. The analysis of recurrent errors proves an effective option, as it enables interactions, stimulates reflections and is a powerful clarification tool (Love and Mammino 1997). The analysis of errors concerning images entails extensive LVI. The most significant incorrect images from tests or from short in-class questions are shown on the board (drawn by the teacher, with full anonymity of the error author/s) and students are invited to compare the incorrect image with the corresponding physical concepts and with the image that had been drawn during explanation, and to identify the incorrect information conveyed by each incorrect detail. This enables additional clarification of concepts and attention to details that may not have been sufficiently grasped during the initial explanation.

The overall analysis of the collected information also shows patterns (e.g., recurrent errors, or recurrent omissions of essential pieces of information), and such patterns lead to inferences. The inferences include that of the essential role of language-mastery for the development of visual literacy (Mammino 2010b) and the importance of LVI to educate students to utilise both communication tools effectively (Mammino 2010c). In the next sections, the importance of language-mastery for the development of visual literacy is taken as a for-granted premise, whereas LVI constitutes the *leitmotiv* of the analysis of the illustrative examples considered.

9.3.2 Selection of Examples from In-Class Practice

Many aspects of in-class practice involve LVI. The examples proposed here comprise the illustration of the operative role of the definition of oxidation number (highlighting LVI in an explanatory context) and the analysis of frequent errors concerning selected diagrams, as they are carried out in the class.

Diagrams depicting physical situations and trends are often perceived as difficult by students, and the answers to questions asking to draw such diagrams may reveal a vast assortment of errors. A typical example from the first year general chemistry course is the graph representing Boyle's law for ideal gases. Two typical examples from the second year physical chemistry course are the diagrams representing the isotherms of a gas and the Carnot cycle. An example from the chemical kinetics component of the third year physical chemistry course concerns the change in the concentrations of the substances involved in a chemical reaction as the reaction proceeds. The more common errors with these diagrams are presented here in detail because of their illustration significance.

Incorrect diagrams can all be tracked down to some degree of LVI failure, as they alter the expected physical meaning. Errors may be due to insufficient understanding of the physical meaning (e.g., the meaning of Boyle's law), or of the correspondence between physical meaning details and image details. Students' resort to passive memorization (memorization without understanding) further complicates the picture. Such a type of resort (although totally unsatisfactory from a pedagogical point of view) is generalised among UNIVEN students, as it is a habit acquired in previous instruction and also a route to try and circumvent the difficulties stemming from poor language mastery and underpreparedness (Mammino 2010b, 2011). The passive memorisation of statements or descriptions and the memorisation of images are dichotomic – sentences and images are memorised separately, as if they were unrelated. Passive memorisation automatically excludes LVI, as LVI requires active mental engagement. In-class discussions of errors in diagrams emphasize LVI to clarify both the physical meanings and their image expressions and to stress the relationships between them.

9.3.3 Example: The Operational Meaning of the Definition of Oxidation Number

Definitions have an operational character, i.e., they provide all the information needed for the identification of the defined item (Mammino 2000). This is a difficult aspect to convey to students who are suffering from poor language mastery and poor familiarity with the basics of the scientific method. In some cases, the operational character can be illustrated through LVI. A typical example is the definition of oxidation number

The oxidation number is a formal charge assigned to each atom on the basis of the conventional criterion that, for each bond, all the electrons are ascribed to the more electronegative atom.

The definition is discussed thoroughly in first year general chemistry and is recalled at the beginning of the electrochemistry component of the third year physical chemistry course, to counter the generalised tendency to memorise some practical rules without attention to the concepts behind them (which often results in

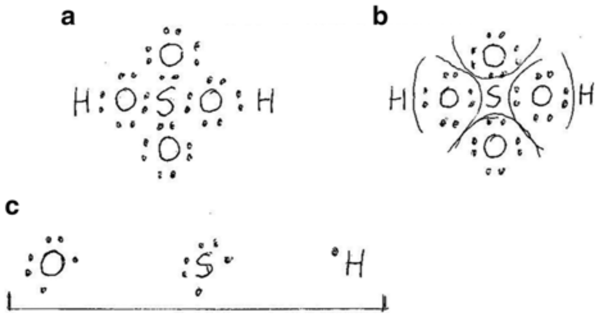

Fig. 9.1 Images utilised in the analysis of the definition of oxidation number. The figure relates to the case of sulphuric acid. (**a**) is the Lewis structure of the molecule; (**b**) shows the assignation of electrons to the more electronegative atom for each bond; (**c**) shows the Lewis symbols of the isolated atoms

Table 9.1 Table utilized for the counting of electrons in the illustration of the meaning of the oxidation number concept

Element considered	Number of electrons counted for that atom in the molecule	Number of outer electrons in the isolated atom	Oxidation number of the element
S	0	6	+6
O	8	6	-2
H	0	1	+1

The table refers to the sulphuric acid molecule (Fig. 9.1)

failure to assign correct oxidation numbers in the "exception" cases). The operational character of this definition is illustrated by reading it and following its "instructions" on images. Several cases are usually considered. Figure 9.1 shows the procedure for the sulphuric acid molecule:

Students encounter difficulties at drawing the Lewis structure of the molecule (consistently with their general difficulties at representing molecules). In addition, they find it difficult to understand how to "count" electrons. Further guidance is usually provided in form of a table to fill (Table 9.1), with the following entries:

- element considered;
- number of electrons counted for that atom in the given molecule, on the basis of the conventional criterion stated in the definition;
- number of outer electrons in the isolated atom;
- oxidation number of the element (from the difference between the values in the third and second columns).

In this way, language (the statement of the definition, the explanations of how we proceed to visualize it) and visualization (how we proceed to implement its "instructions" on the Lewis structure of the molecule) complement each other.

9.3.4 Example: The Graph Representing Boyle's Law

The graph of Boyle's law – a classical inverse-proportionality hyperbole – could be expected to be viewed as simple and straightforward. Yet, a surprising variety of errors is encountered in the large-enrolment (e.g., 420 in 2012, 510 in 2013) first year group. Errors in which random attempts to reproduce something (whatever) fail to provide even the farthest approximation to the target (with figures reproducing anything, from the shape of a p orbital to the heating curve of water, from the planetary model of the atom to the crystal lattice of sodium chloride) are not considered here, because they probably correspond to an absence of efforts at learning rather than to difficulties with concepts or with imagery (although, in some cases, they correspond to extreme language-related difficulties determining total understanding failure). The cases in which the figure shows something that somehow recalls what was encountered in the lectures on ideal gases (even if not Boyle's law) have a considerable probability of being indicators of difficulties at relating physical concepts and their image representations.

Figure 9.2 shows the most frequent errors among the answers that provide a graph. At a first approximation, they can be grouped into the following categories:

(i) Graphs recalling the correct shape, but not relating it to the correct variables on the axes, like in Fig. 9.2a, indicating P/V versus T. Other cases report the variables as V versus P, P versus T, T versus P, 1/V versus P, or even P versus P, like in Fig. 9.2b, where the added comment highlights major problems with diagram-reading. Figure 9.2c is an extreme case in which the indicated variables are not associated with the variables utilised in the description of gas states, and Fig. 9.2d an extreme case misplacing the graph in the cartesian plane.

(ii) Attempts to reproduce the shape of the graph, but not attaining a standard hyperbole, most likely because of combined visual literacy and manual dexterity problems, like in Fig. 9.2e–g. Figure 9.2e corresponds to a widely-spread tendency to approximate as many part of a diagram as possible to straight lines.

(iii) Graphs showing rising curves, like in Fig. 9.2h.

(iv) Graphs showing straight-line segments with various orientations, like in Fig. 9.2i–p.

These errors show difficulties with the understanding of the meaning of Boyle's law (whose statement is memorised passively) and its expression through a diagram. The incorrect selection of the variables on the axes relates to inadequate understanding of the fact that P and V are the variables considered, while T is constant. Curves different from a hyperbole relate to inadequate knowledge of the correspondence between the mathematical equation of inverse proportionality (PV = constant) and its representation.

Figure 9.2i, k, l, besides being incorrect because of the shape of the graph, highlight one of the biggest challenges encountered by students on drawing graphs – establishing what happens in the vicinity of the axes, or whether a certain curve

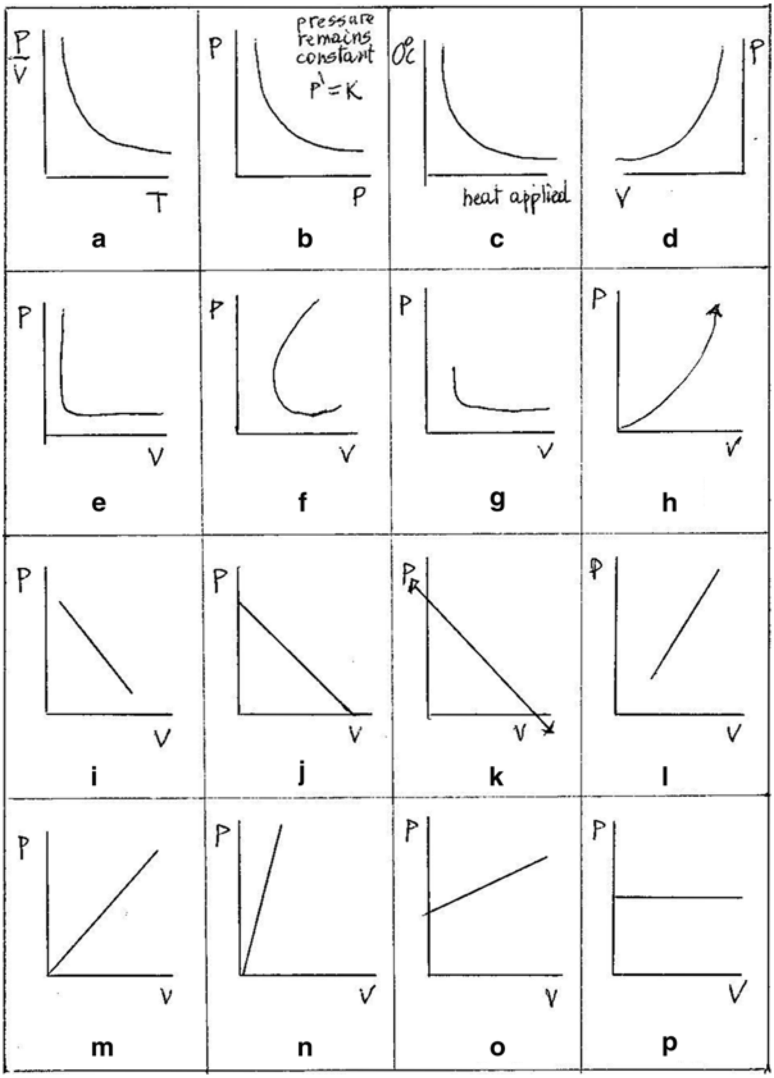

Fig. 9.2 Frequent errors concerning the diagram of Boyle's law

encounters an axis. Failure to establish it leads to graphs in which the part near the axes is ignored (Fig. 9.2i, l), or guessed (Fig. 9.2k). Because of the recurrence of such errors, these features are given specific attention both when first introducing a graph and when analysing errors.

Some answers do not show graphs on a cartesian plane, but represent other images recalled from in-class activities or from other sources. They may relate to inadequate familiarity with the fact that laws that can be expressed through

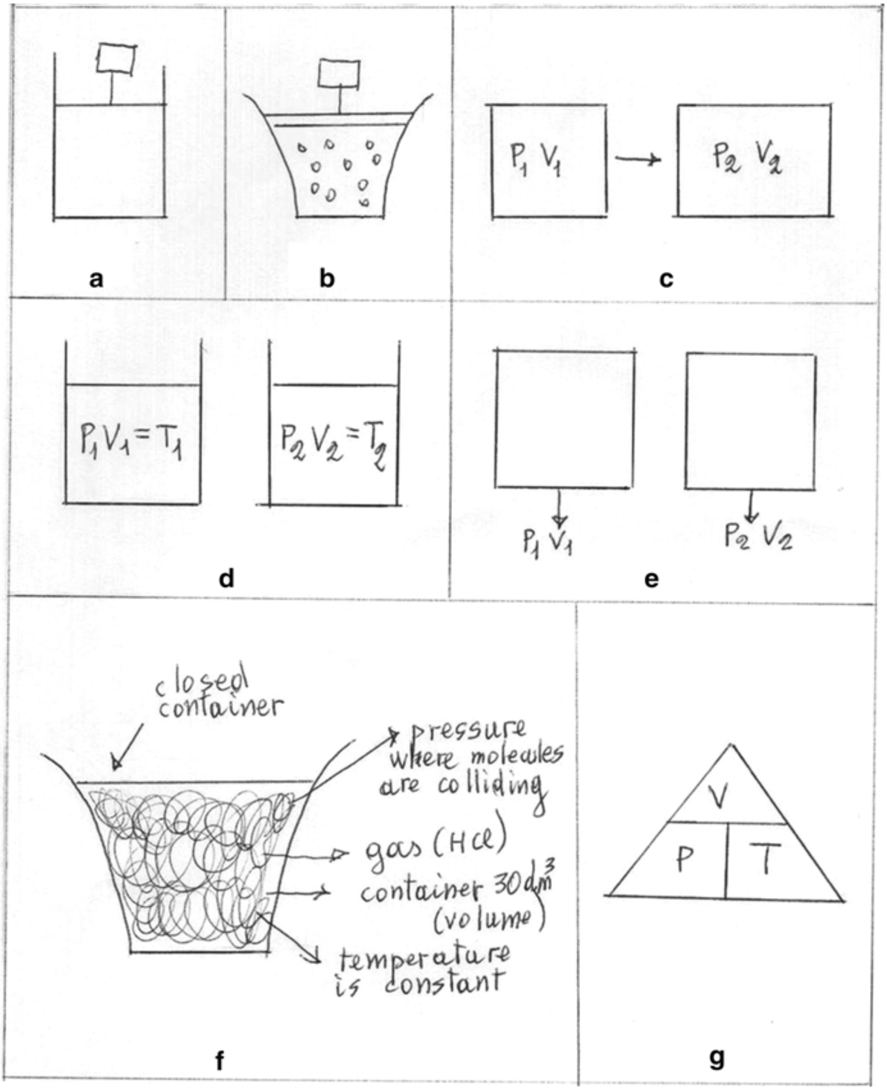

Fig. 9.3 Selected errors concerning the diagram of Boyle's law, in which the images do not consider a graph on a Cartesian plane

mathematical equations can also be represented through graphs, or to failure to grasp the meaning of images that were drawn on the board when presenting experimental features.

Figure 9.3 shows some examples. The drawing may be limited to a single container (Fig. 9.3a), sometimes including the representation of molecules (Fig. 9.3b), or attempt the representation of the initial and final states (Fig. 9.3c–e). The idea that states with different volumes might be visualised by containers with different sizes is absent from Fig. 9.3d, e, suggesting absence of basic comparisons

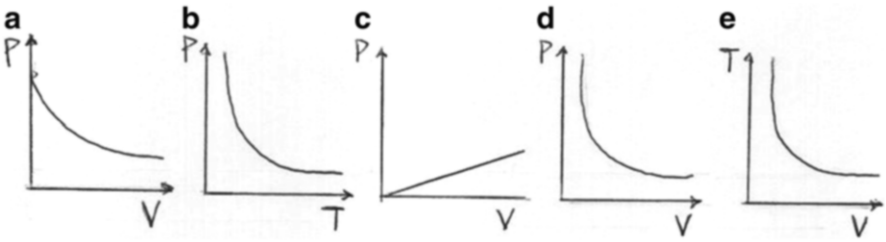

Fig. 9.4 Images proposed for students to select the correct representation of Boyle's law in a recent test

(frequent also in answers through words). Erroneous expressions of the ideal gas state equation, frequently appearing on problem-solving, may surface also in image annotations (Fig. 9.3d). Some drawings may be more difficult to interpret or to address, above all if it is difficult to guess their possible derivation; it is the case of Fig. 9.3f, whose meaning is obscure, or Fig. 9.3g, showing a partition-of-areas between the state variables (P, V and T) that does not correspond to any physical meaning and has no identifiable pedagogical value, but that students must have seen in some source.

A remarkable difference is observed between the cases when students are asked to draw the diagram and the cases when they are asked to recognise a correct diagram from within a set of proposed ones. The former case demands active engagement, thus depending more extensively on LVI, while the latter can more extensively rely on visual memory and is totally independent of drawing dexterity. For instance, students in the large 2013 first year group were asked to select the correct diagram among the five shown in Fig. 9.4; out of 509 students, 356 chose the correct answer (d), 71 chose c, 44 chose b, 24 chose a, 12 chose e and 2 did not answer.

9.3.5 Example: The Isotherms of a Gas

The isotherms of a gas illustrate its behaviour at various temperatures; they are drawn on a PV diagram, and each curve corresponds to a given temperature. On introducing the diagram, the explanation shows how to draw it, relating each detail to its physical meaning and trying to turn the exercise into a collaborative drawing. The exercise requires considerable time, but it is necessary because the comparatively higher complexity of the diagram requires consideration and understanding of a number of features. It involves extensive LVI. The main steps are illustrated in Fig. 9.5:

(a) After drawing the axes and attracting students' attention on the two variables (P and V), the contour of the region that will correspond to the transition from gas to liquid (liquefaction) is faintly outlined in a different colour (Fig. 9.5a),

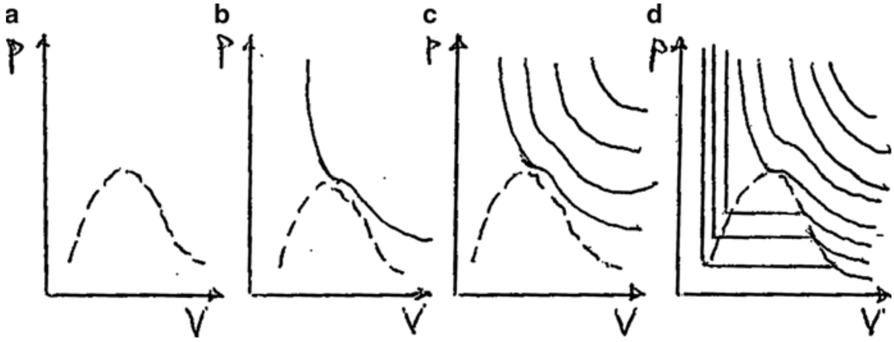

Fig. 9.5 Illustration of the convenient steps to show how to draw the diagram of the isotherms of a gas. Explanation of the steps in Sect. 9.3.5

with the explanation that outlining it from the beginning facilitates correct drawing of the curves.

(b) The isotherm corresponding to the critical temperature (T_c) is drawn (Fig. 9.5b), explaining that it marks the separation between two different kinds of behaviour, i.e., the possibility of liquefaction through sole compression without lowering the temperature for $T < T_c$, and the impossibility of it for $T > T_c$.

(c) The isotherms corresponding to temperatures higher than T_c are drawn (Fig. 9.5c), drawing enough of them to include at least 3–4 pure hyperboles and explaining that, for $T > T_c$, the behaviour increasingly approaches that of an ideal gas as temperature increases.

(d) The isotherms corresponding to $T < T_c$ are drawn, starting from larger volumes and considering to decrease the volume (moving from right to left on the diagram). The liquefaction region corresponds to horizontal segments (Fig. 9.5d). As part of the interaction, students are asked to state the meaning of the horizontal segments, first in mathematical terms (V decreases but P remain constant) and then in physical terms, discussing how this corresponds to liquefaction. After the curve being drawn reaches the left boundary of the liquefaction region, students are asked to decide what happens to the volume if we increase the pressure. After at least one of the students arrives at the inference that the volume will not change significantly (since only the liquid phase is present, and liquids are not compressible), they are asked to decide how the curve should express this (through a vertical line).

Attention is also drawn on practical aspects like the fact that the isotherms should not intersect the y axis (because the intersection would correspond to zero volume, what is absurd) and that they should not intersect each others, because they correspond to different temperature values.

Quite often, students are asked to draw the isotherms diagram in class interactions or tests, and also to answer the same questions discussed during the explanation, about the physical meaning of different features of the diagram. The combination of a question asking for the diagram and questions asking for aspects

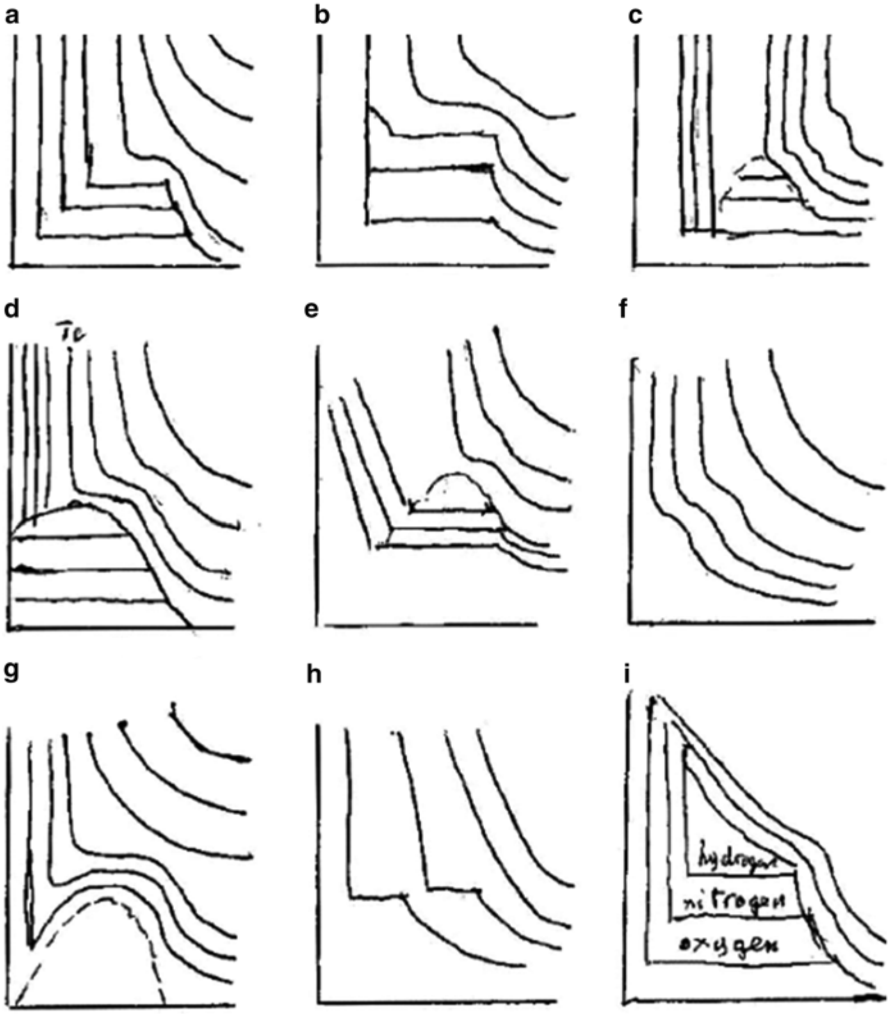

Fig. 9.6 Frequent errors concerning the diagram of the isotherms of a gas

of its interpretation is particularly apt to highlight students' level of conceptual understanding and their ability to relate concepts to their representation and vice versa. Errors are frequent, also because the complexity of the diagram makes passive memorization impossible and, therefore, correct drawing depends primarily on understanding.

Figure 9.6 shows some of the most frequent errors in drawing the diagram:

(i) Fusing together the larger-volume part of the isotherms for $T < T_c$ (Fig. 9.6a).

(ii) Fusing together the part of the curves in the vicinity of the y axis for $T < T_c$ (Fig. 9.6b).

(iii) Disconnection between the horizontal segments of the liquefaction region and the part of the curves in the vicinity of the y axis, sometimes accompanied by fusing together of the larger-volume part of the isotherms for $T < T_c$ (Fig. 9.6c).
(iv) Horizontal segments encountering the y axis, and vertical lines disconnected from them (Fig. 9.6d).
(v) Negative slopes of the straight lines in the vicinity of the y axis, implying that they will encounter the y axis, for $T < T_c$ (Fig. 9.6e).
(vi) Absence of the part corresponding to liquefaction (Fig. 9.6f, g).
(vii) Horizontal lines corresponding to only one P value (Fig. 9.6h).
(viii) Other combinations of lines. Figure 9.6i shows a case in which each line is indicated as corresponding to a different gas.

The discussion of the errors in drawing the diagram is integrated with the discussion of the errors in the answers about the physical meaning of the diagram's features. Selected answers to the questions "Explain the reasons for the region with horizontal segments" and "Explain the reasons for the vertical lines in the region close to the y axis" are reported below. The answers to the latter question are preceded by #, to identify them. When the answer corresponds to one of the diagrams reported in Fig. 9.3, the diagram is mentioned in parentheses after the answers. Several answers are reported, to outline a tentative picture of the situation. The answers are reported as they were written (without spelling or grammar corrections) to document the extent of language-mastery inadequacies, as this is the major cause of the difficulties encountered by students. The information provided in the previous explanation of how to draw the diagram and Fig. 9.5 constitute adequate reference to identify the conceptual errors in the reported answers. Answers 1 and 2 suggest reasonable understanding, but language-related difficulties prevent a complete expression of the concepts. Answer 3 shows an attempt to recall from passive memorisation, but with incorrect identification of the part of the diagram corresponding to the memorised sentence (the incompressibility of the liquid is the reason for the vertical lines). Answer 4 identifies the correct reason for the horizontal lines, but not for the vertical lines. Several answers fail to recognise that P remains constant in correspondence to the horizontal segments (5–9) and that V remains constant in correspondence to the vertical lines (5–7). Some answers recall that the vertical lines correspond to the liquid state, but without identifying that V is constant although P increases (9, 12). Answer 10 reproduces general statements without close relationship to the diagram or to the questions given. Answer 11 does not identify the fact that the vertical lines correspond to the liquid, not to the gas. Answers 12–14 highlight deep conceptual confusions not only on the isotherms, but on other issues (e.g., saying that a gas "expands horizontally" does not have a meaning); meaningless answers are often testimonials of language-mastery inadequacies so profound that the student fails to grasp the basics of the concepts. The answers just considered are the following:

1. # *The vertical lines shows that the gas has changed into liquid and liquid is incompressible unlike gas. So the liquid now does not behave like gas and*

follow the Boyle's law when you compress the gas more and more the lines become vertical it does not change.

2. *# This is because the gas is completely liquefies, is when volume of gas is less, then as pressure can be applied further* (Fig. 9.3b)
3. *When all gas has been condensed to liquid, it became very difficult to decrease the volume of the liquid, that reasons of the horizontal segments.*
4. *The region with horizontal lines represents the increase in pressure at constant volume, there is a decrease in temperature. # Vertical lines in the region close to the y axis represents the decrease in volume with increase in temperature.*
5. *The region with horizontal segments shows that when the pressure increases the volume decreases while the temperature remains constant. # The vertical segments on the y shows that the pressure increases and the temperature remains constant as the T_c which is the critical temperature does not change.*
6. *The region with horizontal segments suggest that the gases were at constant volume. # The vertical lines in the region close to the y axis suggest that the pressure was constant.*
7. *The region of the horizontal segments is that when the pressure of the gas increases the volume of the gas will increase but when the pressure is decreases the volume of the gas will not decrease. # The vertical lines is allow the volume to be increased if the pressure increases, it always favours the volume of the gas. It allows the critical temperature to raise the volume and the pressure of the gas when the temperature is higher.*
8. *The reason for the horizontal lines is because the volume remains constant, the water is either solid or liquid. And none of the gas is condensed to liquid.*
9. *The horizontal lines or segments means there is a decrease in volume and an increase in pressure. # The vertical lines in the region close to the y axis means there is an increase in pressure and there is water liquid.*
10. *In real gases isotherms are different for different gas, they must be determined experimentally; in ideal gases, isotherms are hyperboles as predicted by Boyle's law. # Real gases do not behave like ideal gases* (Fig. 9.3c)
11. *# Vertical lines account for the high pressure, the gas behaves non-ideally* (Fig. 9.3e)
12. *The horizontal segments shows that the gas is in the gas state and pressure and volume are not the same. # The vertical lines in the region close to the y axis shows the liquid state* (Fig. 9.3g)
13. *In the isothermal conditions gas expands horizontally when the work done is being done by the system. # The vertical lines shows that gases are closely in contact with each other due to the isothermal forces among them* (Fig. 9.3i)
14. *Because gas is not compressible. Gas is a real solution, with same composition in all the parts. Because gas can mix with each other in any proportion. # Because there is no pressure with the absence of gas.*

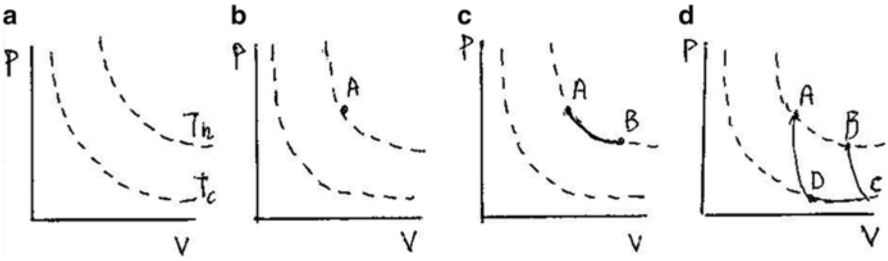

Fig. 9.7 Illustration of the convenient steps to show how to draw the diagram of the Carnot cycle

9.3.6 Example: The Diagram Representing the Carnot Cycle

The diagram of the Carnot cycle appears to be challenging above all because students try to memorise and approximate an overall shape without considering the meaning and individual appearance of each line. At explanation level, the correct way of drawing the diagram is shown in detail in relation to the corresponding physical meaning of each line (Fig. 9.7).

The first piece of information is that the Carnot cycle operates on an ideal gas and works between two different temperatures; therefore, the two isotherms are drawn as general isotherms for an ideal gas (hyperboles corresponding to the hotter (T_h) and cooler (T_c) temperatures; Fig. 9.7a). This way of starting is fundamental to try and prevent many of the more frequent drawing errors. The exercise then proceeds in a sort of collaborative way: selecting an initial point (A, Fig. 9.7b) on the T_h hyperbole, asking where should be the next point (B, Fig. 9.7c) if we consider an isothermal expansion (i.e., a volume increase without changing the temperature); then asking where should be the third point (C) if we consider an adiabatic expansion (recalling that temperature decreases during an adiabatic expansion) and where should be the fourth point if we consider an isothermal compression (D, whose abscissa should be between that of A and that of B). D and A are finally connected through a line representing an adiabatic compression (Fig. 9.7d). The mutual positions of the points are further stressed considering the relative positions of their coordinates on the axes (V_1,P_1 for A; V_2,P_2 for B; V_3,P_3 for C; V_4,P_4 for D). It is also stressed that none of these lines is a straight-line segment. Allowance for drawing-dexterity limitations is made by informing students that, should they not manage to draw sufficiently curved lines for some of the processes (more frequently, the isothermal compression), they should add the comment that they are aware that C–D (or another line) is not a straight line and that the straight-line appearance is due to drawing difficulties; if such comment is added, the line is not considered incorrect on grading.

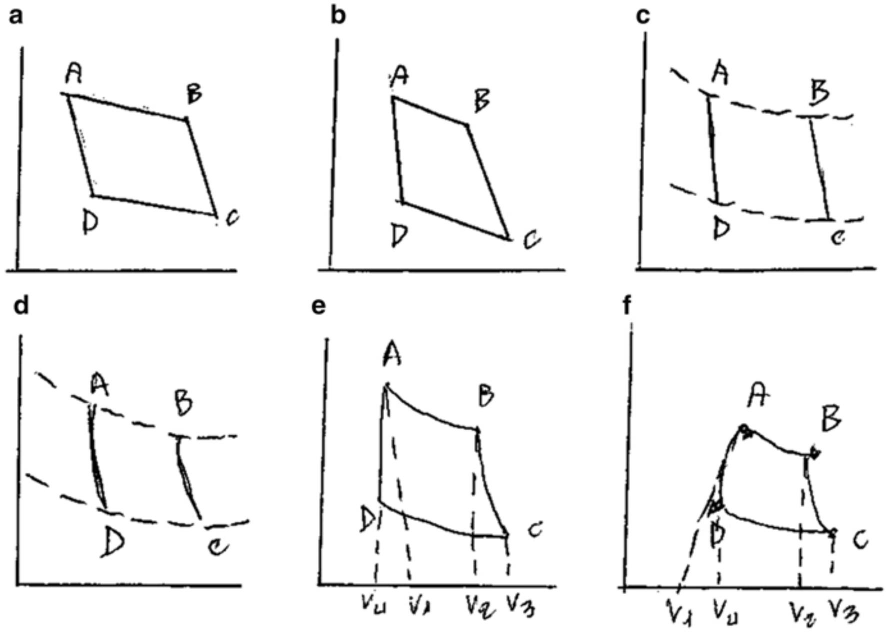

Fig. 9.8 Frequent errors concerning the diagram representing the Carnot cycle

A question asking students to draw the Carnot cycle is included frequently (not every year, but often enough) in second year class interactions or tests. The more frequent errors are shown in Fig. 9.8:

(i) Drawing straight-line segments to produce a regular (Fig. 9.8a) or irregular (Fig. 9.8b) quadrangular shape. These cases do not relate to drawing-dexterity limitations, as the straight-line segments are drawn with the help or a ruler, i.e., purposely;
(ii) Drawing isotherms that will encounter (Fig. 9.8c) or do actually encounter (Fig. 9.8d) the y axis (hyperboles do not encounter the axes);
(iii) Not selecting point D correctly, and then drawing non-vertical dotted lines from D, A and C to show correct relative positions of the corresponding coordinates on the volume axis. In Fig. 9.8e, the leaning dotted lines try to show that $V_4 < V_1$ (which is in any case incorrect); in Fig. 9.8f, they try to show that $V_1 < V_4$, although point D is set to the left with respect to point A.

The errors testify to lack of integration between language (the explanation of the meaning of each line) and visualization (how each curve corresponds to specific information and conveys it). Post-test sessions focus on the correspondence between diagram-features and physical meaning and on graphical aspects like the behaviour in the vicinity of the axes that would be extrapolated from some of the incorrect graphs.

9.3.7 Example: Concentrations of Substances as a Chemical Reaction Proceeds

Basic understanding of what happens to the concentrations of reactants and products during a chemical reaction is fundamental prerequisite to any chemical kinetics discourse. Experience across years indicates that this is a problematic issue (although this information should be part of already-acquired knowledge). Therefore, detailed discussions about the nature of chemical reactions and its implications for the concentrations of the substances involved are conducted as an introduction to the chemical kinetics component of the third year physical chemistry course. The relevant aspects are first considered verbally (interactively), guiding students to recall that:

- The beginning of the reaction corresponds to time = 0.
- Reactants are consumed during a chemical reaction. Therefore, their concentration is highest at the beginning of the reaction and decreases as the reaction proceeds. The decrease with time is usually non-linear. The concentration does not always drop to zero at the end, as the reaction may reach equilibrium with a significant concentration of reactants still present.
- Products are formed as a result of the reaction. Therefore, they are not present in the very start of the reaction, and their concentration increases as the reaction proceeds. The increase with time is usually non-linear.

After this preliminary review, students are asked to draw concentration-versus-time diagrams. Errors are frequent despite the prior review. Figure 9.9 shows the most common ones.

Some errors highlight difficulties at identifying what happens in the vicinity of the axes, as in diagrams showing an asymptotic behaviour close to the y axis (Fig. 9.9a) or starting from a position away from the y axis (Fig. 9.9b) for the concentration of a reactant versus time, or starting from a value greater than zero for the concentration of a product versus time (Fig. 9.9d, e). The analysis of the errors makes reference to the information outlined in the preliminary review and emphasises the following aspects:

- The meaning of "time = 0" as the very beginning of the reaction, and the fact that, in the graph, it corresponds to a point on the y axis.
- The selection of the correct point on the y axis for time = 0: a point in the positive part of the y axis, corresponding to the initial concentration, when a reactant is considered; and the origin, corresponding to zero initial concentration, when a product is considered.
- Whether it is possible that a concentration tends to infinity (assuming that we are not inside a black hole!). Figure 9.9a implies an initial concentration of the reactant tending to infinity, and its analysis extends to the consideration of the meaning of drawing an asymptotic behaviour in the vicinity of the y axis. Figure 9.9e, f imply an infinite growth of the concentration of a product as the reaction proceeds. These aspects are given particular emphasis because they relate to the important issue of the reasonability of values, which is often recalled on discussing answers to numerical problems. Conceptually, a concentration tending

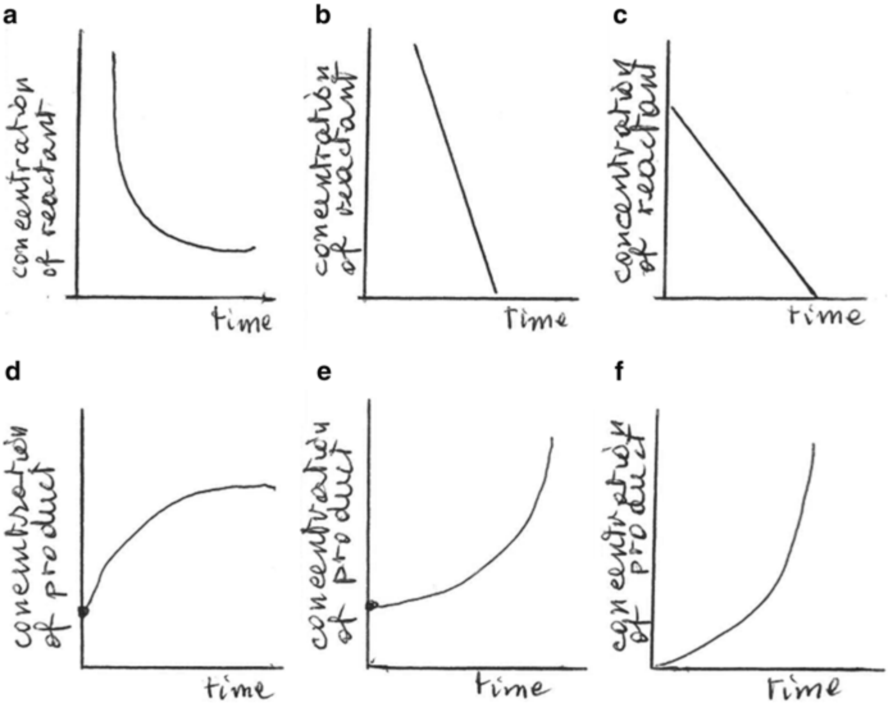

Fig. 9.9 Frequent errors in the representation of what happens to the concentrations of reactants or products during a chemical reaction

to infinity is not very different from answers in which students find absurd values because of some calculation errors (e.g., concentrations of thousand, or even tens or hundreds of thousand, moles per litre) and accept them. That the discussion of diagrams provides opportunities to stress values-reasonability criteria adds to its overall pedagogical significance.

9.3.8 Manual Dexterity and Communication Through Images

An aspect that needs to be considered to complete the picture resulting from the analyses in the previous section is the diffuse inadequate development of drawing manual dexterity. This is different from the ability to read and understand a figure: it requires the manual ability to draw lines, to plan a figure so that it fits in a certain space and its parts maintain reasonable proportions, to join parts correctly, and to draw each detail correctly. It is probably one of those abilities that need to be fostered at an earlier age, as it proved extremely difficult and basically unsuccessful to try and foster it within a tertiary level science course. In extreme cases, it leads to inability to plan a diagram based on experimental values so that all the values available fit into the graph page.

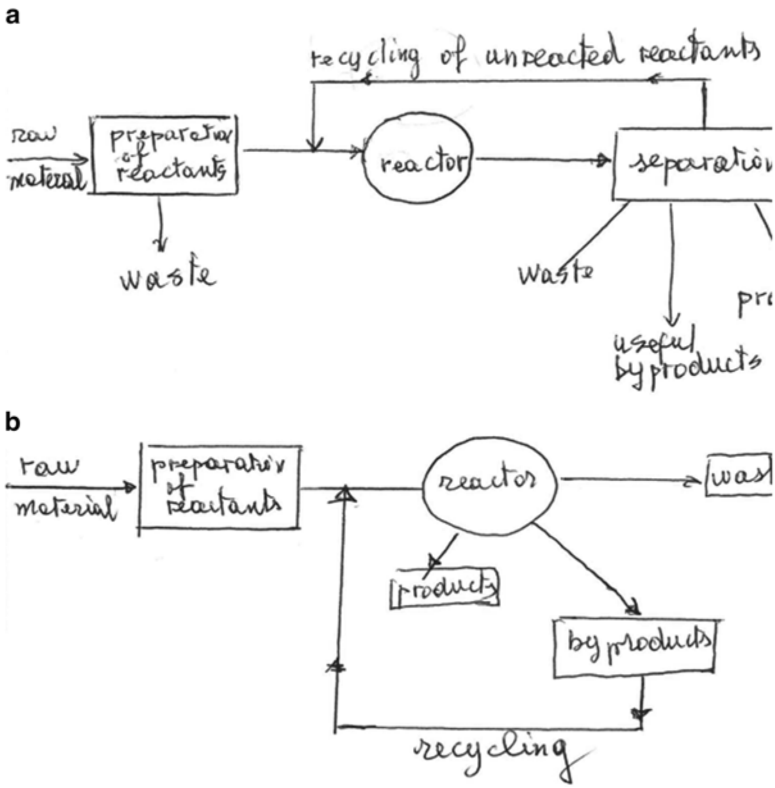

Fig. 9.10 Representation of a prototype chemical process. (**a**) A standard diagram. (**b**) An incorrect diagram from a student's answer (errors for this type of diagram are comparatively rare)

The errors in many of the cases considered in Figs. 9.2, 9.3, 9.6, 9.8, 9.9 and 9.10 may be at least partially ascribable to poor manual dexterity, suggesting that minimum dexterity may be prerequisite to the ability to associate the details of an image to scientific or technical information. This is most likely related to the general importance of hands-on experience: only by being able to draw something can one catch all the details of an image and their significance. Manual dexterity appears essential for the identification and drawing of details like those of the isotherms diagram. It may also determine the ability to "proof-read" at least the most straightforward aspects of an image, while drawing it – for instance, counting the number of bonds formed by each atom in a stick-and-ball representation of a molecule to ensure that they correspond to the atom's bond-formation ability (something that many students fail to do, even at second or third year level, in drawing models of molecules). The absence of actual proof-reading images while drawing them is fully parallel to the absence of actual proof-reading answers expressed through language in works like tests or lab-reports. It appears reasonable to associate the former with inadequate drawing manual dexterity and inadequate VLI handling abilities and the latter with inadequate language mastery – all preventing the feasibility and efficacy of proofreading.

Inadequacies in manual dexterity may also contribute to the frequent failure of the attempts to passively memorise and reproduce diagrams, mostly by hampering the reproduction of memorised images. In extreme cases, the failure extends to easily memorisable diagrams. An example of diagram that students memorise easily and mostly reproduce without errors is the representation of a prototype chemical process (Fig. 9.10a). The comparative ease of memorization is probably related to the fact that the diagram implies some blocks with simple shapes, and no mathematical meaning is associated with individual lines. However, when the manual dexterity is particularly poor, the reproduced diagram may become absurd. Figure 9.10b shows a case in which the separation of the components of the stream leaving the reactor is omitted and recycling refers to the by-products; discussion with the student showed that he knew that the reactor outlet stream must be separated and that the unreacted reactants are the substances recycled, but he failed to associate these pieces of information with the details of the diagram that he was drawing.

9.4 Discussion

LVI can become a powerful teaching instrument, capable of enhancing the clarification of many aspects of a given topic by reinforcing the explanation provided by each of the two communication forms. It is a tool that is managed by the teacher, in terms of when and how to utilise it, and of how to stimulate students to identify and grasp all the aspects involved.

Training students to convert images to information expressed through words/sentences and vice versa is an effective way to guide them to learn how to read images and to better reflect on the information expressed through words. In the case of diagrams, the conversion is more straightforward for diagrams expressing comparatively simple mathematical relationships. For instance, the statement of Boyle's low, its mathematical equation (PV = constant) and the diagram representing it can be converted one into the other fairly easily. Students do not encounter many problems when the inter-conversion is presented in the class. The errors appearing when they draw the diagram on their own are more likely related to poor manual dexterity, or to attempts to passive memorization completely divorced from attempts to read or understand the diagram and to understand the law.

Difficulties increase considerably with diagrams representing physical concepts more complex than a single mathematical relationship. It is the case of the diagrams of the isotherms of a gas (Fig. 9.5), where the diagram involves many details, each of them requiring clear understanding of its physical meaning. Easily memorisable diagrams are often reproduced correctly, but students fail to explain them. It is the case, e.g., of phase diagrams of pure substances (chemical thermodynamics), which most students draw correctly, while very few manage to provide an explanation of their meaning, or even a description of their appearance.

The major problem, and the major cause behind the so-far lower-than-expectation benefits of the in-class systematic association of visualization and language, is the generalised tendency to passive memorization. Equating learning to passive memorization is a sad inheritance of secondary school instruction. It is largely recognised (e.g., Fleish 2008; Mtshali and Smillie 2011; Reddy, Kaniee, Diedericks and Winnaar 2006) that secondary school in South Africa is failing to provide learners with the tools that, altogether, constitute the "epistemological access" (the ability to learn further). The tools that are not adequately developed comprise functional literacy, visual literacy, logical thinking, and other abilities related to independent or creative thinking. Counteracting passive memorization is one of the greatest challenges in a context like UNIVEN (Mammino 2011). Insisting on LVI by asking students to "read" what they draw (to explain its meaning) or to draw something that is explained first through words (when expedient), proves a viable route to foster students' active attention. On the other hand, its efficacy is limited by diffuse students' perceptions about what is important and what is not in the class. Most students want to memorise diagrams or figures; they also want to memorise sentences; but they memorise them as separate items, because the passivity of memorisation does not allow connections between them (connections require reflections and, therefore, active engagement). The same attitude about what is important in the class determines other types of behaviour. Students tend to consider important only what is written on the board, because it is something that can be copied and subsequently memorised. Therefore, many students systematically do not pay attention to verbal explanations, because these have no function in a passive way of learning. In the large-enrolment first year group, some students may even walk out when the major component of the classroom activity is interaction, whether focused on concepts or involving diagrams and other images.

Changing attitudes requires a huge paradigm shift in students' perceptions about learning, which requires time to be realised, like a sort of maturation process developing through years. The number of students who achieve the awareness that learning requires participation and understanding is still small at second year level, increases slightly at third year, and extends to the majority of students at postgraduate level. Therefore, in a context like UNIVEN, a tool such as LVI (or any other tool aimed at students' active participation) has a long-term impact rather than showing short-term results.

The difficulties encountered at the tertiary level highlight the importance of appropriate interventions at secondary level to ensure that students develop more active views about learning. However, the current situation of secondary instruction in South Africa is not conducive for such interventions because of a variety of factors, first of all the shortage of qualified secondary-school science teachers. Moreover, the interchange between persons involved in tertiary-level science teaching and secondary school teachers is so far limited. Improvements would require innovative routes for communication or interactions between educators involved in tertiary-level science teaching, educators training secondary school teachers within educational programmes, and currently in-service secondary school teachers. Then the findings about issues like the roles of LVI, or about other approaches important for science education, could have fallout helping the upgrading of secondary school science teaching and, consequently, the learning abilities of students entering universities.

9.5 Conclusions

The search for optimal balance between communication through language and communication through visualisation in the classroom aims at maximizing the benefits of both. Diagnosed learners' difficulties highlight the dependence of the acquisition of visual literacy on language mastery. On the other hand, emphasizing the interplay between the two communications forms whenever suitable is beneficial both to the development of visual literacy and to the development of language mastery, and contributes to foster active learners' engagement. It would be important to initiate this emphasis and training from the pre-university level, as the level that builds the foundations of learners' learning skills, learning habits and epistemological access.

Previous experience in a given context provides valuable guidelines about important features, like which images require more detailed explanations, both in terms of showing how to draw the images and in terms of underlining the physical meaning of each detail. However, the in-class interplay between explanation through language and through visualization requires the continuous alertness of the teacher, to identify the most suitable responses to the aspects that surface from interactions and to design apt images or formulate apt sentences on-the-spot. The development of this type of competencies could become part of teachers' training, taking into account that competencies are better learnt hands-on, i.e., by doing the job. On the other hand, further research would be important to provide a sufficiently broad range of case-studies to constitute references for teachers' training and in-class activities.

References

Alexander, N. (Ed.). (2005). *Mother-tongue based bilingual education in South Africa: The dynamics of implementation*. Cape Town: Salty Print.

Benson, C. (2004). *The importance of mother tongue based schooling for educational quality*. 2005/ED/EFA/MRT/PI/9.

Brock-Utne, B., & Hopson, R. K. (Eds.). (2005). *Languages of instruction for African emancipation – focus on postcolonial contexts and consideration*. Cape Town: CASAS.

Brock-Utne, B., & Skattum, I. (2009). *Languages and education in Africa: A comparative and transdisciplinary analysis*. Oxford: Symposium Books.

Brooks D.T. (2006). *The role of language in learning physics*. Ph.D. dissertation, State University of New Jersey.
Brown, B. A., & Ryoo, K. (2008). Teaching science as a language: A 'content-first' approach to science teaching. *Journal of Research in Science Teaching, 45*(5), 529–553.
Carré, C. (1981). *Language teaching and learning: Science*. London: Ward Lock.
Davies, F., & Greene, T. (1984). *Reading for learning in the sciences*. Edinburgh: Oliver and Boyd.
Fang, Z. (2006). The language demands of science reading in middle school. *International Journal of Science Education, 28*(5), 491–520.
Fleish, B. (2008). *Primary education in crisis: Why South African school children underachieve in reading and mathematics*. Cape Town: Juta & Co.
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.
Gilbert, J. K. (2008). Visualization: An emergent interdisciplinary field of practice and enquiry in science education. In J. K. Gilbert, M. Reiner, & M. Nakhlekh (Eds.), *Visualization: Theory and practice in science education* (pp. 3–24). Dordrecht: Springer.
Harre, R. (1970). *The principles of scientific thinking*. Chicago: Chicago University Press.
Heugh, K. A. (2009). Into the cauldron: An interplay of indigenous and globalised knowledge with strong and weak notions of literacy and language education in Ethiopia and South Africa. *Language Matters, Studies in the Languages of Africa, 40*(2), 166–189.
Love, A., & Mammino, L. (1997). Using the analysis of errors to improve students' expression in the sciences. *Zimbabwe Journal of Educational Research, 9*(1), 1–17.
Mammino, L. (1994). *Chimica viva*. Florence: D'Anna.
Mammino, L. (1995). *Il linguaggio e la scienza*. Turin: Societa' Editrice Internazionale.
Mammino, L. (1998a). Explorando los empleos de las imagines en la enseñanza de la química. *Anuario Latinoamericano de Educación Química, X*, 54–59.
Mammino, L. (1998b). Selección y discusión de las «imagines químicas» y de sus caracteristicas. *Anuario Latinoamericano de Educación Química, XI*, 123–126.
Mammino, L. (1999a). Explorando los empleos de las imagines como instrumiento de enseñanza interactiva. *Anuario Latinoamericano de Educación Química, 12*, 70–73.
Mammino, L. (1999b). La chimica come area ideale per l'educazione al linguaggio della scienza. *Edichem '99: Chemistry in the Perspective of the New Century*, 212–230. Bari (Italy).
Mammino, L. (2000). Il ruolo delle definizioni nell'insegnamento delle scienze. *Scuola e Cittá, 1*, 25–37.
Mammino, L. (2003). *Chimica aperta*. Florence: D'Anna.
Mammino, L. (2008). Teaching chemistry with and without external representations in professional environments with limited resources. In J. K. Gilbert, M. Reiner, & M. Nakhlekh (Eds.), *Visualization: Theory and practice in science education* (pp. 155–185). Dordrecht: Springer.
Mammino, L. (2010a). The essential role of language mastering in science and technology education. *International Journal of Education and Information Technologies, 3*(4), 139–148.
Mammino, L. (2010b). The mother tongue as a fundamental key to the mastering of chemistry language. In C. Flener & P. Kelter (Eds.), *Chemistry as a second language: Chemical education in a globalized society* (pp. 7–42). Washington, DC: American Chemical Society.
Mammino, L. (2010c). *Interplay, interfaces and interdependence between visual literacy and language mastering, as highlighted by chemistry students' works* (pp. 16–20). XXV: Anuario Latinoamericano de Educación Química.
Mammino, L. (2011). Teaching chemistry in a historically disadvantaged context: Experiences, challenges, and inferences. *Journal of Chemical Education, 88*(11), 1451–1453.
Mammino, L. (2012). Focused language training as a major key for bridging the gap between secondary and tertiary instruction. In D. Mogari, A. Mji, & U. I. Ogbonnaya (Eds.), *ISTE international conference proceedings* (pp. 278–290). Pretoria: UNISA Press.
Mammino, L. (2013). Teacher-students interactions: The roles of in-class written questions. In M.-H. Chiu (Ed.), *Chemistry education and sustainability in the global age* (pp. 35–48). Dordrecht: Springer.

Mtshali, N., & Smillie, N. (2011). Many of our kids can't read or write: Study shows pathetic state of primary school education. *Sunday Time*, June 29.

Munby, A. H. (1976). Some implications of language in science education. *Science Education, 60*(1), 115–124.

Muralidhar, S. (1991). The role of language in science education: Some reflections from Fiji. *Research in Science Education, 21*, 253–262.

Norris, S. P., & Phillips, L. M. (2003). How literacy in its fundamental sense is central to scientific literacy. *Science Education, 87*, 224–240.

Norris, S. P., & Phillips, L. M. (2008). Reading as inquiry. In R. A. Duschl & R. E. Grandy (Eds.), *Teaching scientific inquiry: Recommendations for research and implementation* (pp. 233–262). Rotterdam: Sense.

Qorro M. (2011, March). *Language planning and policy in Tanzania: When practice does not make perfect*. Paper presented at the 8th LOITASA Workshop, Cape Town.

Reddy, V., Kaniee, A., Diedericks, G., & Winnaar, L. (2006). *Mathematics and science achievements at South African schools in TIMMS 2003*. Pretoria: HSRC Press.

Rubanza, Y. I. (2002). Competition through English: The failure of Tanzania's language policy. In K. K. Prah (Ed.), *Rehabilitating African languages* (pp. 39–51). Cape Town: CASAS.

Smith, K. J., & Metz, P. A. (1996). Evaluating student understanding of solution chemistry through microscopic representation. *Journal of Chemical Education, 73*(3), 233–235.

Sutton, C. R. (1992). *Words, science and learning*. Buckingham: Open University Press.

Sutton, C. (2003). Los profesores de ciencias como profesores de lenguaje. *Enseñanza de las Ciencias, 21*(1), 21–25.

Wellington, J., & Osborne, J. (2001). *Language and literacy in science education*. Buckingham/ Philadelphia: Open University Press.

Chapter 10
Visualizations in Popular Books About Chemistry

John K. Gilbert and Ana Afonso

Abstract Three issues have gained a higher saliency in discussion about chemical education in recent years. First, the recognition of the importance of chemistry in all aspects of life – personal, social, economic. This has carried implications for the range of themes on which provision of chemical education is desirable. Second, not only has formal chemical education been recognized as being less successful than would be hoped, but also the inadequate provision of informal chemical education for adults has become apparent. Third, there has been a growing awareness that individuals of all ages learn more, and more willingly, from carefully constructed materials in the form of a narrative that is meaningfully augmented by visualisations. This chapter focuses on popular books about chemistry and the role of visualisation in their use in formal chemical education.

Keywords Textbook • Popular books • Visual representations • Chemistry • Formal science education • External representations • Analogies • Symbolic representations • Text segmentation • Special contiguity principle • Tables • Figures

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10.1 The Role of Popular Books in Formal Chemical Education

10.1.1 The Nature of Popular Books About Chemistry

Popular books about chemistry are those intended to communicate general or specific aspects of chemistry to an audience who are assumed to have a limited range of knowledge of the topics being addressed (MacPherson and Della Sala 2008). There is also the implicit assumption that they are not intended to be used as a core component of formal chemistry education, that is, as textbooks. A major theme of this chapter is a challenge to such an assumption and to suggest some conditions under which they may be helpful in formal chemical education.

Such books have four general characteristics. First, they are relatively cheap, which encourages their widespread purchase by individuals. Second, they are available at a wide range of outlets, not only bookshops and via the internet, but also at airports, railway stations, supermarkets. Third, and another theme of this chapter, is that, in order for them to be useful, their authors must have taken care to communicate complex ideas effectively, bearing in mind the nature of the 'intended audience' for each such volume. As we will show, the careful use of visualisations is a key component to their success. Four, being mainly under the control of the reader, the pace and manner of use of such a book can be varied to ensure maximum learning.

10.1.2 The Possible Use of Popular Books in Formal Chemistry Education

The provision of formal chemical education, that which is provided on a systematic basis within the framework of a prescribed curriculum and the attainment of which is subject to summative assessment, currently faces a number of major challenges.

The traditional purpose of school chemical education has been to provide a necessary preparation for the future study of the subject at university level. In short, it has been 'chemical education towards more chemistry'. The emphasis has been on learning the body of basic concepts that defined the subject. Whilst some attention has been paid to the use of these concepts in the design and production of technological applications, little time has been devoted to the personal and social implications of these technologies, perhaps because these were not known at the time. Over the years the audience for school chemistry has steadily broadened until the basic purpose addressed has become to provide 'chemical education for all'. In this curriculum, much greater emphasis is placed on the chemical technologies and their implications. Meanwhile, the provision of 'chemical education towards more chemistry' continues to be made. The tension between these two sets of purposes could be eased by the systematic development of new materials on specific themes for the use of students and teachers.

While the purposes for chemical education have been slowly evolving over the last century or so, research and development in chemistry and the chemical technologies *per se* have raced ahead at an ever-increasing pace. This means that the importance of some older concepts have diminished (often to zero e.g. 'normality' in quantitative chemistry) and that of newer ones have risen (often very quickly e.g. those used in 'nanochemistry'). Older and simpler chemical technologies have decreased in importance (e.g. the 'Blast Furnace') while others have risen rapidly (e.g. the production of antibiotics). As all this has been going on, much greater insights have been developed into both the positive social implications of the introduction of some chemical technologies (e.g. the elimination of small pox) and the negative social implications of others (e.g. the pollution of rivers). The pre- and in-service education of chemistry teachers has not generally been able to keep pace with all these changes.

In addition to the purposes and content of the chemistry curriculum, the basic assumptions about how students learn have also changed over recent years. The idea that successful learning involved the acquisition of an identical copy of what is being taught (the basic assumption of 'behaviourist' psychology) is gradually giving way to the recognition that students learn by relating what they are being taught about a subject to what they already know that might be relevant to it (the basic assumption of 'constructivist' psychology). As the curriculum is still largely structured on the 'behaviourist' assumption – lots of content has to be 'covered' rapidly with little time for assimilation. This leads to a disinclination to carry on learning the subject when that becomes optional i.e. at the end of 'compulsory schooling'. Whilst the implications of constructivist psychology are gradually being absorbed by educationalists, help for students in assimilating new and often complex ideas is needed.

Popular chemistry books can help address these challenges. Imagine a teacher, having to facilitate the learning of a class, all of whom need to understand the ideas involved in 'chemical education for all' whilst some are also focused on 'chemical education towards more chemistry'. A broad introduction to all aspects could be provided on a 'whole class' basis. However, popular chemistry books that focused on technological applications and implications would enable the 'generalist' students to focus on that aspect, whilst books that focused on the minutiae of core ideas could be of particular use to the 'specialist' students. Lastly, and perhaps most importantly, popular chemistry books, those of a high quality, being under the control of the reader, should lead to improved learning of those aspects of the curriculum that a student found especially interesting or challenging. They will be at their most effective when they can be used without the necessity of access to a teacher.

In a recent paper we have identified, from the literature and from our own enquiries, the general features of popular chemistry books that might increase their use as learning resources (Afonso and Gilbert 2013). This chapter is primarily devoted to an examination in somewhat greater detail of two further desirable aspects i.e. the inclusion of visualisations in the text, for these support the forming of mental models of ideas, and linking of those visualisations to the accompanying text.

10.2 Visualisation

In everyday language, a visualisation is something that can be seen. This meaning is retained in many educational contexts, where it is otherwise called ‘external representation’. The word is, however, used in some publications to mean ‘seeing in the mind’s eye’, otherwise being called ‘internal representation’. In this chapter, the first of these two meanings – ‘external representation’ – is intended throughout.

Because they are so widely used in conveying and creating meaning, a range of broad categories of visualisations/external representations are in general use. These broad categories are: the gestural, concrete/material, verbal, visual, and symbolic. In use, these categories overlap, for example when speaking about a concrete representation or when drawing a gestural representation. The broad categories now briefly discussed in turn and the scope of their potential contribution to popular chemistry books evaluated.

10.2.1 Gestural External Representations

These are movements, mainly by the hands and arms, intended to convey the shape of an object e.g. of the DNA molecule, to refer metaphorically to something e.g. the direction of action of a force, to emphasise a meaning e.g. the regularity of an event, to emphasise the passage of time e.g. ‘this happened before that’. They can only be partially conveyed in a static and visual form as pictures or sketches in popular chemistry books, and so are currently little used therein. They would, however, fit well within the genre of ‘cartoons’ and ‘comic books’.

10.2.2 Concrete/Material External Representations

These are used to represent the three – dimensional nature of a structure by depicting the entities involved, their spatial or temporal distance from each other, and their angular relationships, all on a scale that permit human visual perception. They are thus either larger than that which they represent e.g. of a virus, or smaller than it e.g. of a building. Visual forms of them – pictures or drawings – can be included in popular chemistry books. Interestingly, the advent of the high memory capacity personal computer has enabled ‘virtual concrete’ visualisations to be appended to such books via CDs.

10.2.3 Verbal External Representations

Speech is used universally as a way of producing explanations, including those of phenomena of interest to science, and conveying them to others. For these processes to be fruitful, an individual must know the nature and meaning of the specialist words involved, the syntax and grammar for the language being used that enables this meaning to be expressed. Dealing with these matters is beyond the scope of this chapter, with one exception: the use of analogies.

An analogy is a statement of the type ‘an X is like a Y’. This means ‘that which is to be explained (an X) is, in some respects and to some degree, like something about which we know more (a Y)’. For Hesse (1966), a useful analogy can be created by splitting the source of it (the ‘Y’) into three parts: the ‘positive analogue’, those of aspects of the comparison which seem capable of giving rise to an explanatory function for X; the ‘negative analogue’, those aspects of the comparison which seem to have no explanatory function, and the ‘neutral analogue’, those aspects of the comparison about which clear decisions cannot be made at the time that the analogy is first created. Gentner (1983) used her ‘structure mapping theory’ to differentiate between analogies in terms of the degree of ‘distance’ between the ‘source of the analogy’ (Y) and ‘that which is being represented’ (X), the extremes being labelled ‘far’ and ‘near’.

Analogies play a major role is all aspects of human understanding: we try to understand something about which we know little in terms of something about which we already know more. This particularly true of chemistry, where all the basic elements of the phenomena being investigated are below the perceptual range of the eye. The problem is multiplied in chemical education, where the analogies used in chemistry to understand natural phenomena have to be themselves understood, a process that itself invokes new analogies! In the case of popular books about chemistry, the issue of communicating intended meaning and of creating understanding by the use of analogies is particularly acute, for there is no teacher available to deal with problems in understanding.

This analysis suggests a number of questions to be raised about the use of analogies in popular books about chemistry. How can an author be sure that readers will know the ‘codes of representation’ that govern the use of analogies i.e. what are the relationships that exist between aspects of a model and the nature of the representation used to depict it? Are analogies always really needed to explain the concepts being addressed? Where they are used, is the balance between ‘near’ and ‘far’ analogies appropriately drawn? Is it likely that readers will be familiar with the sources of the analogies used?

10.2.4 Visual External Representations

The range of generic types of external representations that are primarily in the visual mode is so great, and the overlap between types so common, that the only way to make sense of these is through involving a taxonomy of them. A good example of such a taxonomy has been produced by Hegarty et al. (1991). They divide visual representations into three broad classes based solely on their appearance. 'Iconic diagrams' are those where:

> 'the spatial relations of the referent object are isomorphic to the spatial relations in the graphic depiction'

Examples are pictures and line drawings.

'Schematic diagrams' are those:

> '--- that depict very abstract concepts and which rely on conventions to indicate both the components and their organisation'

Examples are Venn Diagrams, flow charts, and linguistic trees.

The third class, 'Charts and Graphs', are those where:

> --- the referent to be depicted is some set of isolated facts or records that are typically quantitative.

Examples are line graphs, polar charts, pie graphs

Visual representations can, and indeed must, have a major role in popular chemistry books for three reasons. First, many kinds of explanation of, for example physical and chemical properties, the entities present in the phenomenon, the causal relations involved, can be succinctly accommodated by such representations. Second, the many types of visual representation available enable several kinds of explanation to be presented in close physical proximity in such a book. Third, because they can augment or be augmented by the surrounding text. The realisation of all three reasons does depend on the reader knowing the 'codes of representation' for each type i.e. the nature, scope, and limitations, of what they can visualise.

10.2.5 Symbolic Visualisations

Symbolic representations are the most highly abstract forms available. If we assign 'reading text' to the visual mode, then there are two types that might be included in popular chemistry books.

The first of these is the 'mathematical equation', which can serve one of three purposes. To build succinct quantitative representations of a topic in terms of the variables which describe its behaviour. To provide a language for the discussion of the relationships involved. To explore, with the use of algebraic manipulation, the possible behaviour of a phenomenon and hence to make predictions that can be empirically tested (Malvern 2000). Because the ability to use mathematics in general and mathematical equations in particular are not as widespread as is desirable in the population, their use in popular chemistry books may be restricted to more 'advanced' books.

The second of these is the 'chemical equation', which, as its name implies, was the special creation of the subject of chemistry as it evolved. There is now an international standard for the contents and form of chemical equations. Again, given the complex nature of 'code or representation' for chemical equations, they are likely to be found only in 'advanced' books.

Wherever visualisations are included in a popular chemistry book, it is likely – indeed desirable – that they are related in some way to the caption that accompanies the visualisation and to the surrounding text.

10.3 Learning from Visualizations

Virtual concrete/material visualisations may well play a larger role in popular books about chemistry in the future, when the practice of attaching computer discs to the covers of books becomes more general, but they do not do so at present, or when all books are available in e-form. We will also not address the gestural, or symbolic modes further. The great majority of visualisations in popular chemistry books will be of the visual type, with the analogies perhaps used in accompanying text. It is these that we will address, reviewing both research on the issue of the quality of visualisations and on the relation between visualisations and the accompanying text.

10.3.1 The Quality of Visualizations

In terms of the intellectual demands of the 'codes of interpretation' for the various types of visual representation, it seems likely that the Hagarty et al. (1991) category of 'iconic diagrams' (e.g. photographs) will be the easiest for the reader to interpret, perhaps followed by 'schematic diagrams' (e.g. Venn diagrams, flow charts) and lastly by 'charts and graphs' (e.g. tables, line graphs). This view has been supported by Pozzer-Ardenghi and Roth (2010). We will address each of these categories in turn in order to identify 'good practice' in their construction.

As 'iconic diagrams', of which photographs are a major example, Pozzer and Roth (2003) suggested that, to be of greatest educational value the background of the photograph should be both distinct and relevant to the phenomenon being portrayed and that multiple photographs of a phenomenon, from different perspectives, were more valuable than single shots.

The literature on the use of schematic diagrams in formal chemical education has been reviewed by (Davidowitz and Chittleborough 2009). They saw the great value of such diagrams as being support for learners in understanding the 'triplet' of chemical representation: the nature of, and relationships between, the macro, sub-micro, symbolic, levels (Gabel 1999). This has been shown to be vital if 'representational competence' is to be achieved (Kozma and Russell 2005). One central aspect of this is the necessity for students to understand the 'codes of representation' of the various generic sub-modes (Chittleborough and Treagust 2008). Two problems in so-doing are that the various sub-forms of diagrams have not been clearly distinguished from each other and hence that the codes of representation have not been defined. These problems will be particularly important when such diagrams are included in 'popular books', for there will be no teachers to address problems of personal interpretation.

Only relatively little seems to be known about how chemical diagrams are inserted in science texts or about how students interpret them. Han and Roth (2006) analysed the function and structure of visual external representations of the particle theory of matter in seventh grade Korean textbooks. They found that iconic diagrams, mainly photographs, were the most prevalent representations. Problems were identified in the design of the schematic diagrams inserted in the textbooks: there was no consistency on the codes of representation used in diagrams (e.g. particles were represented by circles or as 'little persons'); different levels of representation were superimposed (e.g. macro on sub-micro); irrelevant features of representations were highlighted (e.g. colour, shape, background); and they emphasised potentially misleading analogies, such as the outcome of role play in which students 'behave like molecules'. Although most of the external representations had captions, only 34.1 % were explicitly associated with the main text. Gkitzia (2011) described how 10th grade chemistry textbooks made use of diagrams and reported several problems: the mostly frequently used types of diagrams represented a phenomenon at a macro level (23.6 %) or at two simultaneous levels, mainly macro and the symbolic (21.8 %), without explicit integration of them; sub-micro level of representation was overlooked (27.9 %) when compared with the other two levels; the interpretation of surface features in the representations were mainly implicit or ambiguous; the majority of diagrams (73.7 %) were not mentioned in the text; about half of the diagrams inserted in the text either were not supported by captions or their captions were problematic. Leites (2008), in a study the visual external representations of chemical bonds in textbooks published in Argentina, also found that the link between text and illustration is scarce, and when captions are presented they only identify elements of the representation. Concerning popular science texts, Dimopoulos (2003) compared visual external representations in the physics and chemistry textbooks for primary school and lower secondary school use with those in press articles. The results show that, although textbooks incorporate more representations than do press articles: in both of them iconic diagrams were the most prevalent (about 85 %); press articles rarely inserted either conventional representations (i.e. schematic diagrams or charts and graphs) or hybrid representations; the main function of the representations was analytical (i.e. to depict the part-whole structural relationship of an entity). Given the status of textbooks in formal education, these studies, taken together, suggest that non-expert readers are little exposed to visual external chemical representations that rely on the interpretation convention for their understanding.

In the absence of definitive guidance on these issues, we suggest that 'good practice' in respect of the design of diagrams would involve: identifying the target population for which the text and representations are intended; limiting the range of types of diagram that are used; providing some guidance on the interpretation of the

Table 10.1 The use of photographs in some Brazilian biology textbooks

Category of photograph	Description of relationship	Frequency (%)
Decorative	Photograph without captions or references in the text	5.4
Illustrative	Photograph with the name of the phenomenon only in the caption	35.1
Explanatory	Photograph with the name and some explanation of the phenomenon in the caption	28.4
Complementary	Photograph with the name of the phenomenon and some additional information not given in the text	38.1

limited range used; requiring readers to answer questions in the accompanying text in order for them to explore their understanding of the diagrams.

10.3.2 *The Relation Between Visualizations and Accompanying Text*

In complex domains such as science, text comprehension is enhanced when visualisations are used: this is the 'multimedia principle' (Mayer 2002). Such visualisations are better understood when the referring text adheres to the following principles: coherence (i.e. the text should only include information that is essential to understand the illustration); spatial integration (i.e. the text needs to be segmented and placed near the illustration) (Mayer 2002), labeling (i.e. the visualization should be clearly and fully labeled) (Florax and Plortzner 2010). Segmentation of the text focuses readers' attention during reading and helps them to identify units of meaningful information. Placing text near the corresponding illustration (the spatial contiguity principle, Mayer (2002), encourages and facilitates readers' mapping of information between the text and visualisation (Florax and Plortzner 2010). When text and the associated visualisation cannot be presented simultaneously, there are advantages of presenting the visualisation first. According to Schnotz (2002), this is because it is impossible to construct a clear mental representation from only reading a text. Therefore, if the visualisation is presented first, the mental image constructed will augment that. Labels, on the other hand, act as signaling techniques, for they contribute to the construction of clear relationships between information in the text and in the visualisation (Florax and Plortzner 2010).

Pozzer and Roth (2003) studied the relationship between photographs (the main type of visualisation included) and text in school biology textbooks used in Brazil. The outcomes are summarised in Table 10.1.

This study suggests that the educational value of visualisations is under-exploited in science education. However, the paper did conclude both that all visualisations should have appropriate captions that are explicitly linked to the accompanying text and that the inclusion in the text of questions relating to the visualisation was desirable.

Considerable cognitive challenges are presented by tables, by graphs, and by the relationship between them. In respect of the use of tables, Eshach and Schwartz (2002, p. 333), in a study of 12 year old children, found that:

> Students based their conclusions on only part of the data; students did not use either efficient or sufficient (additional) visual representations; students did not apply mathematical operations efficiently; students referred to or built a context to the problem

These problems seem to be no respecter of age or educational attainment, for, as Farquhar and Fraquahar (1891) (quoted in Wainer (1992)) puts it so delightfully:

> Getting information from a table is like extracting sunlight from a cucumber

At the very least, these problems suggest that 'good practice' in the design of tables should be adhered to. Wainer (1992) suggests that every table should: have a self-evident purpose in communication, such that the titles and order of rows and columns should make sense; include data that has been simplified to as great an extent as is possible; be designed so that summaries of rows and columns could be readily prepared. Even where this is done, students would need to know the 'codes of interpretation' for tables. This increased visualisation is helped by the availability of diverse sub-forms of the graph. Tufte (1983) identified four canonical forms of graph:

- Data maps. The positions of objects and events are represented in a specific geographical space. For example, the location of iron-ore mines in Western Australia;
- Time series. Specific values of some measurement are represented as a function of time. For example, the rate of a chemical reaction over a period of time;
- Space-time narrative. The status of objects or events is represented as a function of both time and space. For example, the evolution of a specific genome as a function of historical time and geography;
- Relational graphics. The variation of one abstract concept with another. For example, the variation of half-life with the atomic mass of a parent element.

All four of these canonical forms seem likely to be used in the various categories of popular books about chemistry.

The incidence and significance of the issues identified earlier in this chapter were examined in respect of two particular popular books about chemistry.

10.4 The Enquiry Conducted

In the light of the above literature review, the research questions addressed were:

1. What types of visual representations are included in two popular chemistry books intended for contrasting audiences?
2. How are these visualisations related to the accompanying text in these books?
3. How suitable do science teachers believe these books to be for use in respect of formal science education?

- What are the implications of (1)–(3) for teachers wishing to use 'popular' chemistry books in formal chemistry education?
  - The first book examined was *CO_2 rising: The world's greatest environmental challenge* (Volk 2008). This chosen because it seemed to fall centrally with the (Afonso and Gilbert 2013) category of

> Chemistry in everyday life. Such books deal with the way that chemistry contributes to an understanding of everyday personal life

and, as such, would be of central importance in an education for 'scientific literacy'

The second book chosen was *'The Periodic Table: Its story and significance'* (Scerri 2006). This book fell into the (Afonso and Gilbert 2013) category of

> History of developments in chemistry. Such books deal with how the subject of chemistry has emerged and developed over the years

Its anticipated readership was said in the Introduction to include both 'undergraduate and graduate students of chemistry' and 'laypersons with moderate scientific background'. This would suggest that it would be of use within formal chemical education, in support of 'chemistry towards more chemistry' as well as by the 'general public'.

Research Questions #1 and #2 were addressed by means of content analysis by the first author. The data for Research Question #3 was drawn by a report on the books produced by well-experienced school chemistry teachers under the guidance of the second author. Research Question #4 plays a substantial role in the Conclusion to the chapter.

10.5 'CO_2 Rising: The World's Greatest Environmental Challenge'

10.5.1 The Inclusion of Tables and Figures

This book only contains seven Tables, which are used as the primary means of communication of facts about carbon dioxide emissions. These facts were evidently aggregated from different sources, but the sources are not cited. All the Tables deal with trends in these facts, with different comparison bases for these trends (see Table 10.1). Although the Tables were not labelled as such – they were just inserted into the text- that text provided an interpretation of the trends shown there.

There are 35 Figures in Volk, distributed by type as in Table 10.2 (see Table 10.3).

The inclusion of 'linear graphs' and 'block graphs' assume that the reader will be able to interpret these forms of visualisation. The visualisation of atoms/molecules at the sub-micro level does enable aspects of their causal behaviour to be explained in the accompanying text, for example the effect of changes in energy availability.

Table 10.2 Table types in Volk

Bases for comparison of facts	No. of tables
Historical events	5
Geographical spread	1
Time of occurrence/measurement	1

Table 10.3 Figures in Volk

Type of figure	No. of figures
Linear graph	14
Visualisations of atoms/molecules in a context	8
Visualisations of atoms/molecules	6
Block graph	4
Picture	2
Linear graph with context	1

Table 10.4 Categories of relationship between visualisations, captions, and text

Category of visualisation	Description of relationship
Decorative	The visualisation is provided without captions or references in the text
Illustrative	The caption only includes the name of the phenomenon represented
Explanatory	The caption includes both the name and some explanation of the phenomenon represented
Complementary	The caption includes both the name of the phenomenon and some additional information not given in the text

Table 10.5 Categories of visualisation/caption/text relationships in Volk

Category of relationship	No. of figures falling within each category
Explanatory	25
Illustrative	8
Complementary	2

The extension of this treatment to include both the sub-micro and the macro level of a phenomenon does, at the very least, enable the relationship between the two levels of representation to be touched upon.

10.5.2 The Relation Between Visualisations and the Accompanying Text

The range of relationships between photograph and text outlined by Pozzer and Roth (2003) can be extrapolated to include all types of visualisations (see Table 10.4).

The 35 Figures in Volk fall into three of these categories (see Table 10.5).

All the three categories used lead to extended treatments of the material being provided in the accompanying text. The most widely used category – Explanatory – is closely associated in the text either with the inclusion of chemical theory, or by an introduction of a simple mathematical treatment, or (and this was the most common form) by an exposition of practical implications of the phenomenon in the everyday world. Where the more restricted category – Illustrative – was used, the follow-up in the accompanying text was even more extensive. On the other hand, the two examples of the Complementary category made such extensive use of the visualisation and its caption that the follow-up in the text was just more diffuse and added little to the knowledge being transmitted.

There was virtually no use made of analogies in the visualisations or in the accompanying text. However, anthropomorphic identities ('Dave', 'Coalleen', 'Oiliver') were given to individual carbon atoms dependent on where they were identified ('in atmospheric CO_2', 'in solid coal', 'in crude liquid hydrocarbon', respectively').

Overall then, Volk made very extensive and good use of visualisations.

10.5.3 Use in Formal Science Education

The teacher who read the book with an explicit intention of evaluating the scope of its use in formal chemical education had taught chemistry in Portuguese schools for 10 years. She possessed a Masters' degree in Physics Education.

For her, one of the two main uses of this book in the context of formal chemical education was to provide her with new or expanded 'subject content knowledge' (Shulman 1987). In particular, she reported that she had learnt:

- 'Where the data about the levels of carbon dioxide in the atmosphere are collected
- What the temporal range of carbon dioxide data is
- Why gases responsible for the greenhouse effect have more than two atoms
- To differentiate between atmospheric additional levels of carbon and the natural carbon cycle in the atmosphere
- The seasonal cycle of plants explains an oscillation of carbon dioxide in the atmosphere in the northern hemisphere
- There is no consensus on what caused the ice-age and why it ended.
- During the cold glacial era the mean temperature of the Earth was 5 °C colder than today.'

We must infer that this additional knowledge would enrich her chemistry teaching.

The other main use of this book arose from the evaluation of it that we asked her to undertake. She proposed to teach students how to read and evaluate such a book, this therefore helping them to become independent learners of chemistry in later life. In addition, she stated the intention to use students' reading of the book as the main vehicle for them to learn about:

> the nature of science, controversial issues (e.g. energy sources of the future), chemical bonding, greenhouse gases and global warming, the prediction and changes in carbon dioxide levels

In respect of the anthropomorphisms already focused on above, the teacher commented that:

> The idea of personifying the atoms was a good one because the author created a narrative. ---it shows that the theme extends beyond the school context. The narrative about the pathways of the carbon atoms was a surprise and increased interest in reading (the book). However some of these descriptions were too long---. ---the book would be understood more effectively if it included a chapter presenting scientific information without relying on the personification of the atoms or the inclusion of superfluous sentences

The conclusion to be drawn is that pedagogic devices, such as the use of anthropomorphisms, is a good idea, but their use must be circumscribed.

The creation of a narrative around a central core issue was seen to be one of its great assets, such that

> Most of the illustrations (the visualisations) are clear, easy to understand and relate directly to the content of the text

This narrative was said to be directly supported by the visualisations. They enabled the dynamics of both individual chemical processes and the evolution of chemical knowledge to be more readily understood. They showed the importance of valid and reliable data in the conduct of science.

10.6 'The Periodic Table: Its Story and Significance'

10.6.1 The Inclusion of Tables and Figures

The book includes 54 tables. Of these, 14 were prepared by the author, 1 being a simplification of an original (Table 3.3: 'Newland's first table of 1864'), and 13 summaries of more complex originals (e.g. Table 3.8 'Schematic form of Hinrichs's argument'). The others, the great majority, were redrawn copies of originals derived either from research papers or subsequent textbooks.

We noted that the titles of the rows and columns in the sequence of tables included in the book reflect the historical progress of research in the field. Five phases can be detected:

- In order to identify the relationship between the properties of the elements, early tables sought to *identify the basis for arriving at a sequence of properties.* Typically, the identity of an element is presented against some number derived from measurement of it and thought to be a critical parameter of it e.g. Table 2.1, where 'equivalent weights' are used. In later cases, the differences between

Table 10.6 Sub-categories of 'Figure' in Scerri

Sub-category of 'figure'	Number
Photograph or reproduction of table	27
Photograph of chemist	17
Relationships	14
Graph	8
Structure	5
Chemist's sketch	1
Equipment	1
Total	73

successive values of such derivative measurements are used e.g. Table 2.4, where the difference between the 'equivalent weights' of chemically similar elements is used.

- In the next phase, the *value of a specific sequence of properties* is explored. Newland's 'Octaves' is an early example (Table 3.4). Interestingly, this exploration is associated with the use of an analogy based on the distances in the planetary system (Tables 3.7, 3.8). With 'atomic mass' firmly established as the basis for comparison, this phase culminates in the preparation of tables in which gaps are left for as-yet unknown elements e.g. Table 4.1 'Mendeleev's spiral table of 1869'.
- In the third phase, the emphasis is placed on the *detailed prediction of subsequently discovered 'missing' elements.* This is exemplified by the tables of properties for gallium (Table 5.1), scandium (Table 5.2) and germanium (Table 5.3).
- With a sequence based on atomic weight established, attention then turned to the *causation of this sequence of properties.* With the discovery of electrons, their initial allocation to specific 'rings' around atoms (e.g. Table 7.1, 'J.J.Thompson's electron rings') was followed by a progressively finer analysis of the electronic structure of rings (e.g. Table 7.5, 'Stoner's configurations of 1924 based on three quantum numbers').
- In the last phase of development of the Periodic Table, attention turned to the temperature and pressure conditions leading to *the creation of specific elements* within the tenets of 'Big Bang' theory.

This evolving story, reflected in the sequence of visualisations and their accompanying text, is not presented and discussed in the book

The range of types of visualisation labelled as 'Figures' is much more diverse than in the case of 'Tables' (see Table 10.6).

The most frequently used type of figure was that of a photograph of a table of data (27 examples), derived either from the original reports of research (e.g. Figure 3.4) or from subsequent entries in textbooks (e.g. Figure 6.5), or redrawn versions of original tables (e.g. Figure 1.10). The second most frequent sub-category was that of photographs of chemists (17 examples). These were all of the (Pozzer and Roth 2003) 'illustrative' type, with the photographs unrelated to the surrounding text, with just two (Figures 5.1 and 10.3) showing professional relationships between chemists. The sub-category of 'relationships' (14 examples) depicts several types of relationships between the elements presented in geometric terms. Examples are: spirals used to show periodicity (e.g. Figures 3.7, 10.1, 10.2); time lines to show sequences of historical events (e.g. Figure 8.9); time lines to show electronic events (e.g. Figure 9.3, 9.5). In eight cases, the Figures included were graphs . These were all of the (Tufte 1983) 'relational graphics' type e.g. Figure 3.10, a plot of atomic volume against atomic weight, Figure 9.6, a plot of calculated and observed first ionisation energies. In all cases, this approach enables the trends within the graphs to be more easily appreciated. The sub-category of 'structures' (five in all) are early attempts, produced by the original researchers, to depict the layout of electrons with an atom and hence to represent the progression of elements in terms of these structures (Figures 8.3, 8.4, 8.5, 8.6, 8.8). The two remaining sub-categories, with one example of each found, are of a chemist's lab sketch of possible results (Figure 8.2) and of a piece of laboratory equipment (Figure 7.1).

10.6.2 The Relation Between Visualisations and Accompanying Text

The Figures and Tables included are usually referred to in similar ways in nearby text, serving to extend and elaborate what is said in the text in one of two ways. First, they sometimes provide the actual meaning of the text e.g. the shapes of the Platonic Solids in Figure 1.1 referred to on p. 1. Second and usually, they elaborate on the meaning of statements in the text. For example, the contribution made by Newlands (Figure 3.5 and pp. 80–82).

However, while the contributions of particular chemists to the evolution of the Periodic Table are always stated and often evaluated, for example that of Henry Moseley (Figure 6.6. and pp. 170–173), the 17 photographs of chemists included in the text seem to serve no explanatory purpose. Almost all are formal, stiff, portraits (e.g. that of Edmund Stoner in Figure 7.3), and one can only conclude from them that all were men and that the fashion of wearing of wigs and beards changed over the years.

10.6.3 Use in Formal Science Education

The teacher who read the book with an explicit intention of evaluating the scope of its use in formal chemical education had taught chemistry in Portuguese schools for 7 years. He possessed a Masters' degree in Physics Education.

As in the case of the Volk book, Scerri produces a strong narrative. Thus he concluded that:

> Explanations are embedded within an historical narrative that allows them to be placed in a period of time and in the context, political or religious, in which they were generated

This narrative was

> ---carefully presented in the currents of thought at the time, (noting) the disputes between different personalities and schools, and pointing to some exaggerations in claiming the originality of models. It also highlighted the importance of the scientific community, local and global, in recognising the author of an idea and in casting others into oblivion, even when the later presented ideas that were later developed

A high proportion of the visualisations included were replicas of, or derived from, originals. This, the reviewer concluded, 'increased the importance of the book'. However, the lack of detail of how data was produced was commented upon, whilst the inclusion of modern visualisations to explain novel theoretical ideas would have been welcomed. It was also remarked that:

> ----the author avoided the inclusion of dense mathematical formalism that would 'drive off' some readers.--- (However) I did feel the need for some mathematical formalism--- this is important when the reader expects something more concrete (than a qualitative explanation).

10.7 Implications of Popular Chemistry Books for Teachers

Drawing general conclusions based on a sample of two is always dubious. This is true in this case, particularly so as the range of types and potential audiences for 'popular' books about chemistry is very large. However, two tentative conclusions do seem justified in this case. First, both the Volk and the Scerri books were built around a strong and sustained narrative that ought to lead to a high level of sustained engagement by whoever chose to read them. Second, both made good use of visualisations in both cases in supporting the acquisition of understanding about complex and demanding ideas.

On the basis of the analysis done, it does seem likely that the books would appeal to different audiences. Volk would be of greatest use within the formal science educational system in providing support for the acquisition of 'scientific literacy' as manifest in an address to the science needed to grapple with a complex problem in today's world. Indeed, this book could serve as the primary sources of information and ideas about 'global warming'. This also makes it very suitable to adult, free-choice use. On the other hand, Scerri seems best suited to meeting the needs for education about the nature of science (NOS) of students who seem likely to take their study of chemistry further. Indeed, both the content analysis and the teacher's evaluation of Scerri point to aspects of treatment of NOS that were implicit but not explicit in that volume.

Whichever book is used and for whatever purpose, teacher will need to be sure that their students understand the all the 'codes of representation' that might be used in such volumes. Indeed, teachers could use such books as a way to teaching students the 'codes of interpretation' for representations, always assuming that they are aware of the need to do so (Schroeder 2011). The authors' decisions to exclude mathematical formulations from these books will have done a great deal to ensure that a focus on the qualitative understanding of ideas is achieved by readers. However, particularly in respect of the Scerri volume, teachers of students who are going to continue with the study of chemistry will need to ensure that the treatment of ideas presented is augmented by quantitative treatment of ideas.

There seems little doubt that most teachers will need to have undertaken some in-service training in respect of the ideas contained in these volumes and in how to make the best use of them with their students. The idea put forward by one of the teacher evaluators', that of running a course on how to learn from such books, is an excellent one. As the ancient Chinese saying has it:

> Give a man a fish and he will not starve today. Teach a man how to fish and he will never starve

So it is with education.

References

Afonso, A., & Gilbert, J. K. (2013). The role of 'popular' books in informal chemical education. *International Journal of Science Education (B), 3*(1), 77–99.

Chittleborough, G., & Treagust, D. (2008). Correct interpretation of chemical diagrams requires transforming from one level of representation to another. *Research in Science Education, 38*(4), 463–482.

Davidowitz, B., & Chittleborough, G. (2009). Linking the macroscopic and sub-microscopic levels: Diagrams. In J. K. Gilbert (Ed.), *Multiple representations in chemical education* (pp. 169–194). Dordrecht: Springer.

Dimopoulos, K. (2003). Towards an analysis of visual images in school science textbooks and press articles about science and technology. *Research in Science Education, 33*, 189–216.

Eshach, H., & Schwartz, J. (2002). Understanding children's comprehension of visual displays of complex information. *Journal of Science Education and Technology, 11*(4), 333–346.

Farquhar, A., & Fraquahar, H. (1891). *Economic and industrial delusions: A discourse of the case for protection*. New York: Putnam.

Florax, M., & Plortzner, R. (2010). What contributes to the split-attention effect? The role of text segmentation, picture labelling, and spatial proximity. *Learning and Instruction, 20*, 216–224.

Gabel, D. (1999). Improving teaching and learning through chemical research: A look to the future. *Journal of Chemical Education, 76*, 548–554.

Gentner, D. (1983). Structure mapping: A theoretical framework for analogy. *Cognitive Science, 7*, 155–170.

Gkitzia, V. (2011). Development and application of suitable criteria for the evaluation of chemical representations in school textbooks. *Chemistry Education Research and Practice, 12*, 5–14.

Han, J. Y., & Roth, W.-M. (2006). Chemical inscriptions in Korean textbooks: Semiotics of macro- and micro-world. *Science Education, 90*(2), 73–101.

Hegarty, M., Carpenter, P., et al. (1991). Diagrams in the comprehension of scientific texts. In R. K. Barr (Ed.), *Handbook of reading research* (pp. 641–668). New York: Longman.

Hesse, M. (1966). *Models and analogies in science*. Indiana: Notre Dame University Press.

Kozma, R., & Russell, J. (2005). *Modelling students becoming chemists: Developing* (pp. 121–146). Dordrecht: Springer.

Leites, M. (2008). Las imagenes sobre enlace quimico usadas en los libros de texto de educacion ecundaria: Analisis deside los resultados de la invetigacion educativa. *Ensenanza de las Ciencias, 26*(2), 153–176.

MacPherson, S., & Della Sala, S. (2008). Reviews of popular science books. *Cortex, 44*, 763.
Malvern, D. (2000). Mathematical models in science education. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education*. Dordrecht: Kluwer.
Mayer, R. (2002). Using illustrations to promote constructivist learning from science text. In A. Graesser, J. Otero, & J. Leon (Eds.), *The psychology of science text comprehension* (pp. 333–356). Hillsdale: Erlbaum.
Pozzer, L., & Roth, W.-M. (2003). Prevalence, function, and structure of photographs in high school biology textbooks. *Journal of Research in Science Teaching, 40*(10), 1089–1114.
Pozzer-Ardenghi, L., & Roth, W.-M. (2010). Towards a social practice perspective on the work of reading inscriptions in science texts. *Reading Psychology, 31*(3), 228–253.
Scerri, E. R. (2006). *The periodic table: Its story and significance*. New York: Oxford University Press.
Schnotz, W. (2002). Towards an integrated view of learning from text and visual displays. *Educational Psychology Review, 14*(1), 101–120.
Schroeder, S. (2011). Teachers' beliefs, instructional behaviours, and student engagement in learning from texts with instructional pictures. *Learning and Instruction, 21*, 403–415.
Shulman, L. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review, 57*(1), 1–22.
Tufte, E. R. (1983). *The visual display of quantitative information*. Cheshire: Graphics Press.
Volk, T. (2008). *CO_2 rising: The world's greatest environmental challenge*. Cambridge, MA: Massachusetts Institute of Technology.
Wainer, H. (1992). Understanding graphs and tables. *Educational Researcher, 21*(1), 14–23.

Part IV
Teachers Supporting Student Learning from Visual Representations

1.1 Introduction

This part consists of three papers, all focused on particular strategies that teachers have used to support student learning from visual representations, in addition to those approaches discussed in earlier parts.

In the first paper, Geelan and Fan (this volume, Chap. 11) present the case for the value of the visualisations made available through computer-based interactive simulations (CBIS) to support inquiry-based learning. They claim that the approach can: motivate students to the learning of science; develop students understanding of key concepts; promote student skills in and knowledge of nature of science; provide opportunities for students to engage in scientific discourse, including argumentation. While such approaches do readily provide varied and valuable access to visualisations associated with phenomena of interest, they also require that teachers behave in accordance with constructivist principles i.e. they are supportive, rather than authoritative, in respect of student learning. With those two conditions met, CBIS can address even strongly held misconceptions, it is claimed. A sequence for the design of a series of lessons built around CBIS is suggested.

The changes that took place as a teacher implemented a series of lessons based on student generated representations is the theme of the second paper, by Parnafas and Trachtenberg-Maslaton (this volume, Chap. 12). The theme was phenomena associated with the transformation of energy. The class was 31 students in Grade 6, who met for 2 h for each of 6 weeks. The students were asked to generate their own representation of what was taking place in various energy-transformation phenomena, discuss these extensively in small groups, gradually coalescing into a whole-class decision on the best representations, followed by consolidation teaching to ensure that the scientific principles had been clearly understood.

Although the students had not engaged in such an activity before, they quickly mastered the ability to discuss their work, and produced a range of representations. The change in the behaviour of the teacher (recorded in observation notes and video recording) from a behaviourist-based approach to a constructivist-based approach, seemed to take place progressively. What this work illustrates are the considerable changes in both student and teacher behaviour that must take if a student-generated representation approach is to be implemented in an hitherto orthodox class.

The students and the teacher depicted in the Parnafes and Trachtenberg-Maslaton (this volume, Chap. 11) chapter seemed to adjust readily to the demands of using representations to depict abstract ideas and to providing support for that transformation. In sharp contrast, the Bamberger (this volume, Chap. 13) chapter is concerned with students who find such transformations very difficult and whose teachers found it the task of supporting them very challenging.

Eight teachers met for 2 h per week over 2 years. Their task was to come to an understanding of how their students learnt and, hopefully, how they could be helped to do so more effectively. The experience of the teachers in tackling this opaque and diffuse task, they came to see, mirrored the experience their students had in class. The teachers gradually came to see the value of representations in the realisation and sharing of ideas through discussion, that ideas could be 'trained together' to produce insights, and that the role of the coordinator (Bamberger) was to patiently support the evolution of these insights and skills.

What this third case study does show is that, whilst some teacher development may be rapid and decisive, as in the Parnafes and Trachtenberg-Maslaton case, this is no means always the case, as here. Bringing teachers to empathise with the problems that students have in learning through representations is the key issue and this will vary greatly in the time and support that it needs.

Chapter 11
Teachers Using Interactive Simulations to Scaffold Inquiry Instruction in Physical Science Education

David R. Geelan and Xinxin Fan

Abstract Inquiry instruction is a well-respected and well-supported teaching approach in science education, although the extent to which teachers are able to implement it in classrooms around the world is somewhat disappointing, despite a strongly expressed desire to do so. Reasons for this include pressures on teachers to 'teach to the exam', over-full curricula, student expectations and some characteristics of teachers themselves. There is a significant body of evidence to show that, where inquiry instruction is implemented by teachers, it is highly effective not only for addressing students' misconceptions and helping them to develop deep understandings of correct (canonical) science concepts, but also for developing students' understanding of the nature of science, evidence and argumentation. Teachers find that they are enabled to engage students in higher-level discussions about the use and evaluation of empirical evidence and to offer students richer, more satisfying learning experiences. Interactive simulations – computer-based visualizations in which students can enter variables and observe the effects – offer significant potential to support teachers in scaffolding inquiry instruction in science. This chapter draws together theoretical perspectives and empirical evidence from the literature and develops an original instructional sequence for the effective use of interactive simulations by teachers implementing inquiry instruction in physical science education.

Keywords Physics • Technology-enhanced inquiry • Dynamic simulation • Interactive simulation • Concepts • Conceptual understanding • Science process skills • Science argumentation • Misconceptions • Conceptual change pedagogy • Teachers

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11.1 Introduction

This chapter is about ways in which teachers can most effectively use computer-based (or, more broadly, 'device-based' – see below) interactive simulations to scaffold students' construction of scientific concepts through teacher-facilitated inquiry learning sequences. It looks at some of the things researchers already know about the goals of science education, inquiry learning and interactive simulations, and then draws these threads together to propose a flexible, dynamic sequence for inquiry learning using interactive simulations.

11.2 Interactive Simulations for Addressing Four Goals of Science Education

Synthesising Hodson's (1990) and the NRC's (2005) learning goals for secondary school science classrooms, we have developed (Fan and Geelan 2013) the following framework of four dimensions for use in categorizing and considering the impacts of interactive simulations in secondary school science education. For each of these dimensions, some of the relevant research evidence about the ways in which interactive simulations can enhance science learning is briefly summarised here:

Dimension 1: sparking motivation to learn science;

Clark et al. (2009) report that many studies support the use of interactive simulations to motivate students in science. Examples of relevant studies include Ketelhut's (2007) study, reporting that students who normally found science boring found learning with interactive simulations more interesting. Students in the research conducted by Klopfer et al. (2004) not only enjoyed the simulations and reported that they would like to learn more using them, but became more confident about their science learning. Escalada and Zollman (1997) showed that, although in this instance there was no significant difference between achievement scores with and without simulations, students believed the tools were valuable for their learning and were motivated in their learning.

Dimension 2: developing conceptual understanding;

As early as the 1970s, Boblick (1972a, b) demonstrated that interactive simulations are at least as effective as traditional instructional approaches such as hands-on lab for the conceptual development of high school students. Zietsman and Hewson (1986) found the same conceptual development effectiveness with Motion Simulation as with science remedial instruction, and Choi and Gennaro (1987) found that the Volume Displacement Simulation in Earth Science had the same effect as hands-on labs, including no difference in results between girls and boys. Russell and Kozma (1994) investigated an interactive simulation in which students could change chemical variables and examine the feedback of these changes. They found that this significantly increased students' understanding of concepts, as well as reducing the number of related misconceptions. In studying students' use of interactive simulations in science classes, research indicates that learning through simulations or based-simulation technology can enhance students' deep understanding of scientific concepts (de Jong 2009; Quellmalz et al. 2009). Interactive simulations are most effective when placed within a broader curriculum unit and supported by scaffolding and teacher support.

Dimension 3: promoting science process skills and understanding of the nature of science;

One of the challenges in science education is to engage students in inquiry and scientific investigative process skills in the classroom. Interactive simulations offer new affordances for enhancing students' science inquiry (Jacobson 2004). Early studies on science process skills found that interactive simulations can capture such phenomena more effectively than traditional approaches and have the potential to spark a desire in students to learn scientific concepts and understand the investigative process. Interactive simulations can also expand and improve classroom inquiry work (Geban et al. 1992; Kinzie et al. 1993; Rivers and Vockell 1987). Making sense of science as a way of knowing and learning about phenomena is described as understanding the 'nature of science', which includes learning science process skills such as observation, questioning, hypothesis formation, exploration, manipulation, analysis and reaching conclusions (Honey and Hilton 2010; Krajcik et al. 1998). In the interactive simulation environment, deeper understanding of scientific concepts occurs as students engage in intensive interactive investigation. Buckley et al. (2006) reported the relationship between the development of science process skills and understanding of concepts in a simulation-based classroom. Students used a software system linking simulations to a genetics unit in text and wrote logs when they interacted with the instructional system to solve science process tasks. In analysis of students' pre- and post-tests, researchers argued that developing understanding of science processes helped students' conceptual understanding.

Dimension 4: developing students' skills in scientific discourse and argumentation and identification with science learning.

Scientific discourse includes scientific language – including numbers and symbols as well as conventions of written communication – through which the science community shares norms, experiments, and results. Students are encouraged to correctly use scientific discourse (Honey and Hilton 2010). When they engage with science and use scientific discourse, students think about whether they are acting as science learners and whether they would like to develop an identity and contribute to science. This is referred to as 'identity in science learning'. It may be thought of as developing an identity of the form 'I am a person who can do science, likes science, enjoys science'. (The complementary goal is to avoid students developing an identity as 'a person who can't do science'.) Discourse is an essential component of such an investigative approach because it is by "talking science" that students come to understand the phenomena that they are investigating (Lemke 1990).

Science education can, in part, be regarded as a process of preparing for future learning and problem solving by developing scientific discourse and identification (Bransford and Schwartz 1999; National Research Council 2005). Few studies have been published on the use of interactive simulations to advance students' scientific discourse or identification with science. Sandoval (2003; Sandoval and Reiser 2004) conducted a simulation-based curriculum unit for the secondary Biology classroom (BGuilE). Students developed scientific arguments as scaffolds to develop their understanding of scientific phenomena. Analysis of the results indicated that scaffolding scientific argument supported their deep understanding of scientific concepts. Rosenbaum et al. (2007) reported a study in which students played an augmented reality game in which they could play scientists as their characters. After analysis of surveys, video, and interviews of the 21 urban high school students they found increasing use of scientific words and discourse in the science classroom. Students also learned more about their own identity as scientists. Squire et al. (2008) analysed students' use of scientific words in the same game and came to similar conclusions.

This framework is not specific to the context of interactive simulations, of course: it is a general way of attending to the different goals and emphases within science education that go to make up an expanded notion of scientific literacy. It is by attending to each of these dimensions at a high level that science education can fulfill its mandate of preparing citizens for scientifically-informed engagement in the significant challenges that the future will present for society.

These findings are summarised briefly here but presented in more detail in Fan and Geelan (2013), with references to many more relevant studies.

11.3 Inquiry Instruction in Science Education

Inquiry instruction is not a new topic in science education. It has been advocated as a promising instructional approach at least since Dewey (1916). Unfortunately, researchers and teachers have found inquiry instruction – as recommended in the (US) National Science Education Standards (NRC 1996), and mandated in most other educational jurisdictions around the world, including Australia and China – to be difficult and time consuming to enact in real instructional contexts. Traditional instructional practices are still the mainstream approaches in science education. Alvermann and Moore (1996) conclude that "traditional teaching practices might prevail because they are what teachers know best" (p. 973). Loucks-Horsley et al. (1998) note that "it is difficult to teach in ways in which one has not learned" (p. 1). Students continue to be involved in memorizing discrete science facts, listening to teacher-centered lectures and conducting 'cookbook' laboratory activities. These approaches tend to be further entrenched by regimes of high-stakes testing, and ironically serve to destroy students' innate curiosity about the world of science.

Inquiry instruction can be described as 'constructivist-referenced', rather than explicitly constructivist (Geelan 1997). Constructivism is a theory about knowledge: that students, with the help of various scaffoldings (including teachers, more knowledgeable peers, necessary materials and tools) actively construct new knowledge in their minds rather than passively absorbing it from an external source. Students come to understand the nature and laws of science during the learning process (Geelan et al. 2002) and learn to succeed in solving both school 'problems' and real-world scientific problems (Wood et al. 1976; Palincsar 1998; Stone 1998). There are several possible theories about learning and teaching that are consistent with that theory about the nature of knowledge, including a variety of perspectives on the role of the teacher. Constructivism has sometimes been seen as minimising the importance of the teacher's role; however this is not an essential characteristic of this theory (or even, really, an implication of it). Inquiry is consistent with constructivism, in that it focuses on learner's knowledge-construction processes and the ways in which teachers scaffold and support those activities. Properly understood, the teacher is absolutely central to effective inquiry instruction – not as a lecturer, delivering 'content knowledge' for students to absorb, but as a professional who makes judgements about what supports and stimuli students need in order to enable their knowledge construction to be as effective and efficient as possible.

Students typically come to the science classroom with a number of alternative conceptual frameworks, which can inhibit their learning and understanding of certain concepts (Driver and Easley 1978; Driver and Erickson 1983; McCloskey 1983). Furthermore, students tend to share a set of well-documented misconceptions (or 'alternative frameworks') (Bryce and MacMillan 2005; Colburn 2000; Falconer et al. 2001; Kloos et al. 2010; Knight 2004; Mazur 1997; Zavala et al. 2007) that they use to explain phenomena in daily life even after they have completed traditional science instruction (Bryce and MacMillan 2005).

Conceptual change pedagogy (Posner et al. 1982) focuses on helping students to switch their allegiance from their existing misconceptions (also referred to as *preconceptions*, *alternative conceptions*, *alternative frameworks*, *naïve conceptions* or sometimes *children's science*) to the 'correct' (i.e. canonical, current best understanding) scientific concepts to explain their experiences. Posner et al.'s (1982) conceptual change pedagogy revolves around the idea that, in order for students to embrace new conceptions, they should feel *dissatisfaction* with their existing conception, and that the proposed new conception – the scientific idea the teacher intends them to learn – should be made *intelligible* (able to be understood by the students), *plausible* (seem to make intuitive sense to the students) and *fruitful* (have the potential to explain not only the phenomena under discussion but other novel phenomena). Inquiry approaches to instruction are broader than simply conceptual change approaches; however the linked concepts of (1) explicit attention to students' development of new concepts and (2) rejection of existing misconceptions are important in understanding the approach to inquiry instruction outlined later in this chapter. One further concept forms part of the necessary background: the distinction between 'open-ended' and 'open-entry' inquiry on the part of students. Some confusion has been observed on the part of both teachers and theorists in the field.

Open-ended inquiry, in which each student can arrive at a different conclusion, is appropriate for 'socio-scientific issues'. For example, a question about whether, on balance, it is better to use nuclear or solar energy (or some blend of both) to better meet Australia's energy needs in the context of climate change is an appropriate context for open-ended inquiry. In addition to the relevant scientific and technological knowledge about the two forms of energy there are economic and social issues that mean there can be a range of valid solutions to the complex, real-world problem. Open-ended inquiry is *not* appropriate to the learning of scientific concepts! It is not acceptable for each student to have a 'private science' with different concepts.

For teaching scientific concepts, then, 'open-entry' is the appropriate form of inquiry. That is, students start with a wide range of questions (which they 'own' – a key feature of inquiry learning) and a wide range of 'naïve conceptions' based on their own sense-making about their life experience so far (including their experiences at school). The inquiry process is then more 'funnel-like', as students, facilitated, supervised and supported by the teacher, converge on a common, shared understanding of the correct scientific concept. We recognise that scientific concepts are canonical in nature – our best available human constructions, tested against the evidence and prone to falsification – rather than necessarily objective truths about the external universe. For the purposes of school education, however, it is important that students learn the 'correct' concept, while also learning something about the nature of science, theories and evidence.

The teaching sequence described later in this chapter is focused on open-entry inquiry learning: while it is possible that interactive simulations could be used as part of the information in an open-ended inquiry sequence into a socio-scientific issue, our concern here is with the teaching of scientific concepts.

Students, in the learning environments designed and created by teachers, participate in inquiry learning through predicting, designing, experimenting, collecting and analysing data, and then making conclusions and creating new questions. Students' capacities for problem-solving are fostered during the completion of the inquiry tasks, particularly through the guidance of teachers. Teachers inspire students to explore the relevant scientific laws in a simulated environment where the teacher is a guide to students' own knowledge-construction and knowledge-testing activities, rather than a source of knowledge to be passively absorbed by students.

Research finds that this pedagogical approach effectively increases students' understandings of scientific concepts as long as students receive enough teacher support (Lee and Songer 2003). This chapter discusses the role of teachers when implementing simulation-enhanced inquiry instruction.

11.4 Interactive Simulations

Interactive simulations are considered by many scientists and science education researchers to be promising technological tools for science instruction (Clark et al. 2009). Interactive simulations include external (as opposed to mental) visualizations, usually computer-based, such as graphics, diagrams, models and animations

(Frederiksen and Breuleux 1988), with which students can interact; for example by entering data, changing settings and observing the results. Interactive simulations can be described as computer-based 'exploratory' applications and considered as representations simulating dynamic systems of scientific phenomena in 'virtual laboratories' (Gilbert and Boulter 1998).

Although interactive simulations have been described as 'computer-based', the rise of tablets and smartphones and the increasing incidence of computing capabilities in a wide range of everyday objects mean that it might be better to talk about these tools being 'device-based'. They are as likely – perhaps more so – to be run on iPads and other tablets, students' smartphones, interactive whiteboards and other devices as on desktop or laptop computers. This notion links with the 'BYOD' (bring your own device) movement (Raths 2012) in educational technology more broadly.

Interactive simulations offer hypothetical, natural, engineered or invented scientific phenomena to students visually (Committee on Modeling 2010). They also support students to observe invisible phenomena beyond the range of the naked eye such as atomic and molecular scale processes as well as allowing visual representation of non-physical concepts such as magnetic field lines (Botzer and Reiner 2005; Gobert 2000).

Interactive simulations provide opportunities for students to learn science through bringing their individual prior knowledge and engaging in experimental practices using new technology tools. Rapp (2005) described three interactive factors influencing learning: cognitive engagement, interactivity and multimedia learning. He argues that the use of multiple media with which students can interact (rather than passively consume) can enhance cognitive engagement.

Issues related to the use of interactive simulations for supporting teaching and learning have been explored in research for over four decades (Smetana and Bell 2011). Interactive simulations typically allow users to interact with visual representations by manipulating or altering experimental data sets and exploring the implications of modifying parameters (Clark et al. 2009).

Six features of interactive simulations have been identified in the literature:

1. High involvement and interaction with users are the primary educational affordances of interactive simulations. They can better support students' learning compared to passive visualization tools and also can ignite and maintain students' interest and motivation.
2. Offering students opportunities to make mistakes and test hypotheses through changing parameters is a process that has the potential to create robust learning.
3. Interactive simulations can convey information in plausible, economically viable ways. Students can experience situations and phenomena that are impossible to observe in traditional classrooms or real time. What is more, this approach aligns with the nature of mental representations and supports the construction of mental models (Brunye et al. 2004).
4. Interactive simulations, as visual representations, enable students to construct individual explanations from their own investigations instead of learning through direct instruction. This allows them to concretize their own images for their own

understanding. Interactive simulations provide opportunities for students to reflect on their learning while they are constructing new concepts.
5. Instant visual feedback is available. This allows students to discuss the results and concepts with their peers and instructors to learn more about concepts according to their own results. Furthermore, this is an effective way for instructors to monitor students' progress and provide support and guidance in a timely manner.
6. Interactive simulations can scaffold students' learning, supporting them to develop concepts, particularly in situations where their prior conceptual knowledge is lacking.

Each of these features is important for fostering students' scientific literacy, and together these things are often (to some extent) missing in current school science education (Clement et al. 1989; Gobert and Clement 1999; Lowe 1993). Given these affordances, it seems plausible that interactive simulations would be highly effective for fostering science learning and enhancing students' scientific literacy.

11.5 Visual Affordances of Interactive Simulations

The third, fourth and fifth of the features listed above all rely, in one way or another, on the visual affordances of interactive simulations. Simulation tools form a subset of the broader class of visualisation tools, and their effectiveness is in part explained by their interactive nature, and in part by their visual affordances.

Gobert (2005) outlines perspectives from cognitive theory about the use of external visual representations in science education. She lists the following implications of visualisation for learning:

- Visual information tends to be presented all-at-once rather than in a sequence through time as occurs with text or speech. (Some forms of visualisation have a more narrative, linear quality, but interactive simulations tend to deliver their information in a single screen.)
- The search strategies used for accessing visual information differ from those for text.
- Visual information offers different perceptual clues for making inferences.
- Some visual representations are more 'visually isomorphic' (Gobert 2005, p. 75) to the objects they represent than are verbal or textual representations – a picture of an object looks more like the object than a block of text describing the object does. This is true for pictures but not, for example, for graphs or diagrams.
- Scaffolding is required in order for students to develop domain knowledge and skills in interpreting visual representations. What is represented may be so obvious as to be transparent for an expert but far from obvious for a novice.
- Learning from visual representations is a constructive process.

Each of these elements can be applied to the visual dimensions of interactive simulations, and these are issues that need to be thought through in order to inform teachers' pedagogical decisions about how to use these tools and how to build students' knowledge and skills in using them for learning.

11.6 Interactive Simulations for Particular Concepts

It is plausible that interactive simulations will be more effective for addressing some concepts than others in the science curriculum. There is little evidence as yet in relation to this question, and much research still to be done. It is plausible that these tools might be particularly effective for addressing topics about which students have strong and instruction-resistant misconceptions (Bryce and MacMillan 2005; Colburn 2000; Falconer et al. 2001; Kloos et al. 2010; Knight 2004; Mazur 1997; Zavala et al. 2007). Our own research has demonstrated effectiveness on a par with traditional instruction for the concepts of chemical equilibrium in chemistry (Geelan and Mukherjee 2010) and force-related concepts in physics (Geelan et al. 2012). The question of which concepts will be best served – in terms of students' conceptual development specifically but more broadly in relation to each of the four dimensions of science education – by teaching using interactive simulations is an empirical question, and a very large one. It will require sustained and programmatic research by those working in the field for some time to answer in any detail, and to date empirical evidence of the effectiveness of these tools is very sparse.

11.7 Teachers Using Interactive Simulations for Inquiry Instruction

Involving students in more interactive activities, rather than simply using visualization tools as aids in traditional modes of representing the world, can maximize the learning benefits students receive. The key theoretical features arising from a constructivist framework are the emphasis on students' active construction of knowledge, the conception of knowledge as a rich network of related concepts and the emphasis on scaffolding –for the purposes of this chapter, focusing particularly on the teacher's role and the affordances of interactive simulations. The (quite preliminary and sparse) literature suggests that where interactive simulations are used effectively in an inquiry learning approach to science teaching, student learning gains are greater (Yager 1996).

It can be challenging for teachers to use interactive simulations for inquiry instruction. Teachers are asked to deal with new classroom and behaviour management issues, resolve technical problems and integrate the technology innovations with existing instructional modes and skills (Varma et al. 2008). It is important to note that we see interactive simulations as an addition to the teaching toolkit, designed to help teachers develop scientific problem solving in their students, rather than as a replacement for existing tools or teaching roles. 'Real' experiments in which students conduct measurements on apparatus on the laboratory will never be obsolete in science education and are an essential complement to computer-based simulations. Chiu (2010) indicates that students are more successful at understanding physical concepts when teachers provide the explanation using simulation software. David Geelan has conducted research into science teacher explanations (Geelan 2012) and these are also an essential part of teaching. Interactive simulations are chosen for the things they do well, not pressed into service to (try unsuccessfully to) do everything in science education.

Constructivist theory suggests that prior knowledge plays a critical role in learning. Teachers need to help students construct new knowledge on the foundations of students' existing knowledge. Boo and Watson (2001) argued that different representations of knowledge introduced by technological visualization tools could confuse students. This suggestion reinforces the necessity for scaffolding students' learning *about* the visualisation tools they will use as well as learning *with* these tools. Just as students learned to read and write text, they need time and support to learn to 'read' visual representations.

Perhaps unsurprisingly, teachers with more experience in facilitating inquiry learning on the part of their students had better student outcomes from inquiry instruction than did teachers with less inquiry experience (Fogleman et al. 2011; Lee et al. 2010). To take full advantage of inquiry instruction with simulations, more experience with inquiry teaching can help teachers to notice students' learning in group activities, interpret the outcomes and readings from the simulation software for students and conduct more effective interventions to support student learning. In addition to experience, teacher professional development training (e.g., workshops, seminars on the application of technology in STEM, workshops on the effective use of visualisation tools) should be provided to in-service teachers to fully realise the value of interactive simulations.

Stieff et al. (2005) proposed two pedagogical approaches based on constructivist theory to support the use of visualization tools. (They also made recommendations about the design of visualisation tools, but the purpose of this chapter is to focus on classroom teaching rather than on the development of new tools.) The first pedagogical approach is *guided inquiry*, which means that inquiry environments play a critical role in the science classroom by supporting students to behave like research scientists (Edelson 2001). The other approach emphasizes the interactive procedures of learning science. The use of visualization tools supports students to build up individual models of scientific phenomena and to develop deep understanding and improve their problem solving skills.

In technology-enhanced inquiry learning, teachers' guidance plays an extremely important role in supporting successful learning (Quintana et al. 2004). This is particularly critical to younger students participating in structured inquiry and guided inquiry (cf. Ginsburg and Golbeck 2004). Studies on technology-enhanced inquiry instruction indicate significant effectiveness when it is strongly supported by teachers (Clements 2002; Plowman and Stephen 2005). Younger students need more help when they experience problems and questions. Scaffolding from teachers can be modified in accordance with students' dynamic thinking and the learning situations that arise in the classroom (Tippins and Kittleson 2007).

Studies have presented reasons for why some teachers do not succeed with technology-enhanced inquiry instruction (Linn et al. 2003; Quintana et al. 2004; Schlager and Fusco 2004; Songer 1996). When teachers attempt to use new technologies to enhance their science instruction, they encounter obstacles including unreliable internet connections, outdated computers, limited instructional freedom, and lack of support from school administrations (Bielaczyc 2006; Slotta 2004; Songer et al. 2002).

The role of a teacher using interactive simulations to support students in inquiry learning of scientific concepts is that of a (professional, active, informed, engaged) guide. The responsibility of such a guide is to be a knowledgeable expert who facilitates students' discoveries, assesses their understanding and inspires students to further learning, in a learning community. Fang (1996) pointed out that a teacher's beliefs should be consistent with his/her perceived teaching role. Pajares (1992) supported the notion that teachers' beliefs influence their perceptions, which in turn affect their practice in the classroom. Teacher education, therefore, has a profound bearing on the effective classroom implementation of simulation-enhanced inquiry instruction.

Teacher professional learning networks and support in understanding and implementing new teaching roles and approaches is advocated in the (US) National Science Education Standards (NRC 1996). Without such support the many pressures on teachers, their attitudes and beliefs, technological constraints, lack of relevant information and reluctance to abandon familiar teaching approaches could hamper effective integration of simulations into physical science classrooms (Chen and Chang 2006). Teacher education in relation to technical skills, applications and particularly pedagogical approaches can support teachers to achieve optimal implementation. The studies of Chen and Chang (2006), Reiser (2004) and Clements and Sarama (2004, 2007) present ways to effectively integrate and guide the use of technology applications in inquiry learning.

Experienced experts should also support teachers' classroom practice and implementation of new approaches in order to help the teachers learn how to select effective interactive simulations for inquiry instruction and develop capacity to use them to complement existing curricula and learning activities in classrooms. Most science teachers understand the benefits of inquiry curricula and are interested in using new technologies to support their inquiry teaching but resist using these approaches without appropriate support. Heath (1992) argued it is difficult to implement interactive simulations for inquiry instruction if there are no appropriate sources of support. Technology Enhanced Learning in Science (TELS), an NSF funded Center for Learning and Teaching, are developing approaches and materials to support teacher professional development for the goal of expanding the use of technology-enhanced science inquiry instruction (Kali and Linn 2007; Varma et al. 2008).

All of these supports are essential if school science education is to fully realise the potential of interactive simulations for inquiry learning of science concepts. The following section, however, refocuses on where 'the rubber hits the road' – the classroom – and outlines an instructional approach intended to support teachers in using these tools more effectively to support student learning.

11.8 An Instructional Sequence for Teacher Facilitation of Inquiry Learning Using Interactive Simulations

There have been laudable earlier attempts to outline instructional approaches for inquiry learning, including those of Jeffrey and Peggy Wilhelm in English education (Wilhelm et al. 2009) and the work of Bell et al. (2005) in science education. This chapter draws on those accounts and the literature around inquiry instruction more broadly, constructivist and conceptual change theory, consideration of the specific affordances for learning of interactive simulations and the authors' own classroom teaching experience to outline an approach to teaching inquiry science lessons using interactive simulations.

The focus of this sequence is on Dimension 2 of the framework outlined earlier – developing students conceptual understanding. It is explicitly aimed at providing students with experience and evidence to (a) support the new scientific concept they are developing and (b) falsify or challenge any misconceptions they hold.

The evidence shows that students enjoy using interactive simulations (Clark et al. 2009), which means that using them can usually be assumed (although further research is needed, particularly into what happens once the novelty wears off) to also address Dimension 1 – student motivation and engagement.

Other simulations and other sequences – particularly carefully rendered 'virtual laboratories' – could be used to address Dimension 3 – the development on the part of students of science process skills. Practice with the skills of conducting experiments and collecting data is important, and one advantage of interactive simulations is the ability to conduct more experiments in the same time compared to a 'real' laboratory. While not all skills can be learned in the device-based environment, sequences and approaches to developing Dimension 3 are definitely something interactive simulations can support.

We would argue that scientific argumentation, in particular, is better conducted between human beings without computer mediation. While Dimension 4 – scientific argumentation and development of identity as a scientist – can plausibly develop in informal ways as students work with interactive simulations, this is one dimension for which other activities may be more effective.

The sequence below, then, focuses on Dimension 2: developing students' rich, flexible use of scientific concepts to understand their experiences and the world around them.

Recent work from one of the authors of this chapter (with collaborators) has shown that in terms of conceptual learning gains, different order of instruction does not yield different outcomes (Fogarty et al. 2012). That is, whether simulations are used before teacher explanations or after, the net learning over all remains about the same. This is heartening news, in many ways, since the technological constraints within many schools might mean that, for example, the computer lab or classroom laptops are only available for one lesson in a week of classes. The teacher has considerable freedom to rearrange the learning activities to fit the constraints of the timetable, while still giving the students rich, effective learning experiences that lead to deep understandings.

With that evidence in mind, then, the following sequence should be understood as dynamic, rather than static. We have listed the elements in order, because it's necessary to choose a means of presenting them. We see this order as logical, and think the final elements listed need to come near the end of the instructional sequence because they draw on the earlier elements, but (a) if it's necessary to, say, switch the second and third activities, that is fine and (b) rather than a linear progression with a beginning, middle and end, sometimes a learning sequence will involve cycling through the middle steps multiple times to ensure deeper understanding.

11.8.1 The Zeroth Step

This chapter is about the use of device-based interactive simulations, but as science educators we would *always* suggest that, if it's at all possible, students should gain experience of the physical phenomena being studied. This is not always possible – one of the affordances of interactive simulations is to allow students to gain access to phenomena that are too large, small, slow or fast to be directly observed in the classroom, and to concepts that are not directly visible in the physical world (such as magnetic field lines). But wherever it is possible for students to lift something, look at it, make measurements, collect data, mix solutions and so on, we would suggest that this is essential. After all, scientific ideas are meant to explain our experience of the world around us, so as far as possible giving students access to direct experience (and asking them to carefully attend to its features) is valuable.

In some cases the phenomena might also be too dangerous to conduct in the classroom, or inaccessible because of distance or other factors. In these cases, video or other media may also be helpful in giving students experiences to use in testing theoretical perspectives. These media are less effective than direct experience, but more effective than no experience. We hope teachers will strive to offer direct experience whenever possible, rather than default to the easier alternative of finding a piece of video on the web. We do, however, have a realistic view of the budgetary and time constraints under which teachers work.

11.8.2 Step 1 – Elicitation and Clarification of Existing Conceptions and the 'Target' Scientific Conception

An initial step in any inquiry teaching sequence is gaining as rich as possible an understanding of the range of conceptions already held by students in the class. By 'conception', we mean a simple scientific idea such as 'force is directly proportional to acceleration (if mass is constant)'. There is a rich literature of student misconceptions in chemistry and a less rich but still strong knowledge of physics misconceptions, and understanding these is part of teachers' professional knowledge, but no class is typical. It is important that the teacher finds ways to have students outline their existing conceptions, and that the teacher understands the range and differences in the class – and not just the ideas of the most extroverted students with the loudest voices! An example of a common misconception in relation to the force example might be 'physically larger objects always require larger forces to yield the same acceleration (if the mass is constant)'.

Whole-class discussions, or small-group discussions with a 'report back' phase to the whole class, can be helpful teaching strategies for eliciting existing concepts from students. Well formulated, detailed questions are the key to such discussions, rather than a broad 'what do you know/think about…?' approach. Brief diagnostic tests can also be valuable, although the goal is to find out what conceptions students hold, rather than simply to determine whether they do or do not already hold the correct scientific conception, and the questions asked should be open-ended enough to allow teachers to understand this. Another possible approach is a predict-observe-explain (White and Gunstone 1992) sequence using either 'real' experiments or interactive simulations, in which students make predictions (which will be made on the basis of their existing conceptions) and observe whether they are confirmed or falsified by evidence.

It is possible that some students will not already have any real concept of the issue under discussion, and in this case learning is more a case of conceptual development than conceptual change. That is, they are (to take a common constructivist metaphor) building the concept in a bare field rather than (to mix a metaphor) exchanging one concept for another. This kind of learning usually occurs more easily than conceptual change, but many of the same kinds of experiences contribute to conceptual learning.

Other students may have amorphous, partially formed conceptions that are not clearly and logically articulated and that may not be internally consistent. One of the dangers of this kind of teaching approach is that students can (a) more clearly and fully understand – and then embrace – their own misconceptions and (b) articulate their misconceptions so compellingly that other students adopt them rather than the scientific conception! Teachers need to be aware of this possibility and guard against it – the goal is to enable students to understand, learn, use and internalise the correct scientific conception.

Conversely, some students may already have a well developed and elaborated understanding of the correct scientific concept due to private reading and learning, experiences with peers, TV programs or a wide range of other learning experiences. These students can be drawn on as a resource by the teacher, and can help to explain the scientific concept and its implications to their fellow students.

Inquiry learning sequences are sometimes conducted as 'mysteries', with the teacher only eliciting student conceptions, and trying to let the scientific concept 'emerge' from the inquiry process. We would discourage this approach, and suggest that rather teachers offer a clear, brief description of the scientific concept as part of a discussion that also includes the student conceptions. Later discussion will attend to making it intelligible, plausible and fruitful (Posner et al. 1982) for students.

11.8.3 Step 2 – Outlining the Predictions and Implications of Students' Existing Conceptions and the Scientific Conception

Scientific concepts are tools for looking at the repetition of events: 'when we do this (under these circumstance) this happens', and then using those repetitions to make predictions about what will happen. Different conceptions are different, at a level deeper than simply that of the language chosen to describe them, precisely because they make different predictions about what will happen. In order to be able to provide evidence to support the scientific concept, and evidence to challenge and falsify the various misconceptions that are held by students, it is necessary to tease out and understand the specific predictions made by each of the 'candidate conceptions' being explored. Sometimes there will be only one major misconception held in the class, so that there is direct competition between this misconception and the correct scientific concept. More commonly there will be two or more alternative conceptions, but there are unlikely to be as many as there are students in the class, or anything like that many: a few different conceptions is most typical.

Requiring students to commit to the predictions they make, in writing, is a valuable teaching strategy, along with asking them to outline how their prediction arises from the conception that they hold. Having them also clearly understand what they will observe if the scientific theory is correct is also a key component of this phase of the process.

11.8.4 Step 3 – Testing Predictions of Competing Conceptions Using Interactive Simulations

Geelan (2013) outlines a learning model developed by Frank Jenkins at the University of Alberta, described as the 'Create, Test, Use' model. It recognises that the goal of learning science is to learn concepts that can be empirically tested using experiments (or, in the present context, tested as models using interactive simulations). Evidence from laboratory activities can be used inductively to help students construct ('create') a concept, or they can be used deductively once a concept is understood in order to 'test' (i.e. provide more empirical evidence to support) a concept. Finally, once a concept has been created and tested, it can be 'used' in the development of further, related scientific concepts.

Being able to test a concept, or create it, requires that students *understand* what the experimental results mean. That is, while the observation might be 'the green solution turned orange when the colourless solution was added', the underlying understanding is 'the colour is due to an acid-based indicator and indicates that the solution has switched from acidic to basic'. That in turn will have meaning for understanding whatever the target concept might be – the role of buffer solutions in pH, for example. It is only as students really understand the meaning of the results – rather than simply following a recipe and recording what there is space for in the table – that they are 'doing science' and developing scientific knowledge.

In the context of interactive simulations this relationship is complicated somewhat by the 'black box' nature of the device-based simulation. Students need to have a level of trust that the simulation *means something* in terms of reality, and that the results it yields are a map of the results the real world would yield if they actually did the experiment. This may well be something that needs to be discussed explicitly with students: How do we know we can trust the results from the simulation? How could we test them? Is internal consistency enough, or would we need to do experiments where we could observe the results more directly?

In this testing step, often there will be two (or more) concepts 'competing' – a common student misconception (or a few) and a canonical scientific concept. In accordance with the conceptual change instructional approach, it is necessary that students be dissatisfied with their existing conception and find the scientific conception intelligible, plausible and fruitful (Posner et al 1982). This will arise if the predictions made by the misconception and the scientific conception are different, and if these predictions are made very explicit for students before the interactive simulation is used. 'If the solution remains green, that supports the theory that [very brief description of the misconception], if it turns orange, that supports the theory that [very brief description of the scientific conception].'

Misconceptions are resilient: it takes more than a single exposure to cause students to switch their allegiance from a misconception that does not satisfactorily explain their experiences to a correct scientific conception that does. This is perhaps complicated further by the 'out' that is offered to resistant students by the simulated nature of the experience: they can always claim that the glitch is in the equipment, not in their own understanding of the concept. Repeated experiences will be required, and discussions among students, facilitated by the teacher (who can provide prompts and questions but should not simply state the 'correct' answer – students are constructing the concept through their testing and interactions) are a very important part of the inquiry learning model.

This need for repeated experiences and exposures likely means that more than one cycle through steps 2, 3 and 4 of this sequence may be required in a single teaching sequence. These can focus on related concepts, or on the same concept in a slightly different context, or using a different simulation tool. Certainly a sequence in which the 'real' experiment was conducted, complemented by a sequence using interactive simulations – one affordance of which is the ability to run many iterations of an experiment in a relatively short time – would be a powerful learning experience.

11.8.5 Step 4 – Clarification of Findings and Linking Results to the Scientific Conception

If the sequence has been well designed and well conducted, and the students 'carried along' at each step in terms of their understanding, the evidence gained from using the interactive simulations – which may include visual observations such as changes of colour, state, pressure or volume, tables of data, graphs or a variety of other forms of information – should have supported the scientific concept and falsified the misconceptions held by students. Note that more than one interactive 'experiment' may be required in order to address the range of misconceptions held in the class.

It is at this step that the scientific concept is 'nailed down' in the minds of students by making very explicit the ways in which that concept explains our experience and makes it possible to make reliable predictions about what will happen. Lingering misconceptions may be addressed through discussion, through teacher demonstrations using either the interactive simulation(s) or a 'real' experiment or through cycling back through earlier steps of this teaching sequence. The goal of conceptual learning is that the correct scientific conception should be *demonstrated* to the students to be sufficiently powerful and useful that they adopt it as part of their sense-making scheme for 'how the world is', or at least for 'how scientists understand the world'.

11.8.6 Step 5 – Further Testing to Develop and Deepen Understanding of the Scientific Conception

In very full and busy science curricula, often there is insufficient time to more fully develop concepts, but at the same time 'concept coverage' – a speedy, exposure-only tour of concepts – does not lead to real, internalised learning. Part of the challenge of teaching is to find an optimal pace, and find ways to include repeated practice and use of concepts. What we might call 'joined-up science teaching' is at least part of the solution.

Despite the structural features of schools which divide science learning into years, terms and units, science learning is very much a connected whole, and both knowledge and skills from one topic are relevant to other topics. The 'use' dimension of the 'create, test, use' sequence involves using a learned concept as a base from which to learn new concepts, and as the concept is being used, students' knowledge and understanding of it will deepen. Conceptual learning does not finish at the unit test.

11.9 Conclusion

Like the other device-based scientific visualisations discussed in other chapters of this book, interactive simulations offer new and valuable affordances to support classroom teachers' teaching of science. In particular, these tools allow teachers to more effectively facilitate students' inquiry learning activities – their ability to actively test both their misconceptions (naïve conceptions) and their developing scientific conceptions against a simulated reality.

When combined with other tools in the teaching toolbox, interactive simulations offer potential to enhance the ways in which students develop understanding of scientific concepts, but also offer opportunities for students to develop knowledge of the nature of science and skills in designing inquiries, gathering, analysing and representing data and drawing conclusions well supported by the available evidence.

We have suggested a flexible, dynamic instructional sequence for teaching science with interactive simulations, drawn from existing literature and research, but much more research remains to be done in classrooms to develop and share powerful approaches to teaching with interactive visualisations. Crucially, this research will involve real collaborations between researchers and teachers, who are already richly engaged in exploring better ways to scaffold and support their students' learning.

We hope the ideas introduced and explored in this chapter will be valuable for teachers who are just beginning to use interactive simulations in their teaching, as well as those who have been doing so for some time and are seeking to deepen and enhance their skills in using these promising new tools to enhance their students' science learning.

References

Alvermann, D. E., & Moore, D. W. (1996). Secondary school reading. In R. Barr, M. L. Kamil, P. B. Mosenthal, & P. D. Pearson (Eds.), *Handbook of reading research* (Vol. 2, pp. 951–983). New York: Longman.

Bell, R. L., Smetana, L., & Binns, I. (2005, October). Simplifying inquiry instruction. *The Science Teacher, 72*(7), 30–33.

Bielaczyc, K. (2006). Designing social infrastructure: Critical issues in creating learning environments with technology. *Journal of the Learning Sciences, 15*(3), 301–330.

Boblick, J. M. (1972a). Discovering the conservation of momentum through the use of a computer simulation of a one-dimensional elastic collision. *Science Education, 56*(3), 337–344.

Boblick, J. M. (1972b). The use of computer-based simulations and problem drills to teach the gas laws. *Science Education, 56*(1), 17–22.

Boo, H. K., & Watson, J. R. (2001). Progression in high school students' (aged 16–18) conceptualizations about chemical reactions in solution. *Science Education, 85*(5), 568–585.

Botzer, G., & Reiner, M. (2005). Imagery in physics learning from physicists' practice to naive students' understanding. In *Visualization in science education* (Vol. 1, pp. 147–168). Dordrecht: Springer.

Bransford, J. D., & Schwartz, D. L. (1999). Rethinking transfer: A simple proposal with multiple implications. *Review of Research in Education, 24*, 61–100.

Brunye, T., Rapp, D. N., & Taylor, H. A. (2004). *Building mental models of multimedia procedures: Implications for memory structure and content.* Paper presented at the 26th annual meeting of the Cognitive Science Society, Chicago Illinois.

Bryce, T., & MacMillan, K. (2005). Encouraging conceptual change: The use of bridging analogies in the teaching of action-reaction forces and the "at rest" condition in physics. *International Journal of Science Education, 27*(6), 737–763.

Buckley, B. C., Gobert, J. D., & Horwitz, P. (2006). *Using log files to track students' model-based inquiry.* Proceedings of the 7th international conference on the learning sciences, International Society of the Learning Sciences, Bloomington.

Chen, J., & Chang, C. (2006). A comprehensive approach to technology training for early childhood teachers. *Early Education and Development, 17*(3), 443–465.

Chiu, J. L. (2010). *Supporting students' knowledge integration with technology-enhanced inquiry curricula*. Unpublished Ph.D. dissertation, University of California, Berkeley.

Choi, B.-S., & Gennaro, E. (1987). The effectiveness of using computer simulated experiments on junior high students' understanding of the volume displacement concept. *Journal of Research in Science Teaching, 24*(6), 539–552.

Clark, D. B., Nelson, B., Sengupta, P., & D'Angelo, C. (2009). *Rethinking science learning through digital games and simulations: Genres, examples, and evidence.* Paper presented at the National Research Council Workshop on Gaming and Simulations, Washington, DC. http://www7.nationalacademies.org/bose/Gaming_SimsCommissioned_Papers.html

Clement, J., Brown, D. E., & Zietsman, A. (1989). Not all preconceptions are misconceptions: Finding "anchoring conceptions" for grounding instruction on students' intuitions. *International Journal of Science Education, 11*(5), 554–565.

Clements, D. H. (2002). Linking research and curriculum development. In L. D. English (Ed.), *Handbook of international research in mathematics education* (pp. 599–636). Mahwah: Lawrence Erlbaum.

Clements, D. H., & Sarama, J. (2004). Hypothetical learning trajectories. *Mathematical Thinking and Learning, 6*(2), 81–89.

Clements, D. H., & Sarama, J. (2007). Early childhood mathematics learning. In F. K. Lester Jr. (Ed.), *Second handbook of research on mathematics teaching and learning* (pp. 461–555). New York: Information Age Publishing.

Colburn, A. (2000). Constructivism: Science education's "grand unifying theory". *The Clearing House, 74*(1), 9–12.

Committee on Modeling, S. a. G. (2010). *Rise of games and high performance computing for modeling and simulation*. Washington, DC: National Academies Press.

de Jong, T. (2009, October 6–7). *Learning with computer simulations: Evidence and future directions*. Presentation to the National Research Council Workshop on Gaming and Simulations, Washington, DC. http://www7.nationalacademies.org/bose/deJong_Gaming_Presentation.pdf. Accessed 15 Feb 2011.

Dewey, J. (1916). *Democracy and education: An introduction to the philosophy of education*. New York: Macmillan.

Driver, R., & Easley, J. (1978). Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education, 5*(1), 61–84.

Driver, R., & Erickson, G. (1983). Theories-in-Action: Some theoretical and empirical issues in the study of students' conceptual frameworks in science. *Studies in Science Education, 10*(1), 37–60.

Edelson, D. C. (2001). Learning-for-use: A framework for the design of technology-supported inquiry activities. *Journal of Research in Science Teaching, 38*(3), 355–385.

Escalada, L. T., & Zollman, D. A. (1997). An investigation on the effects of using interactive digital video in a physics classroom on student learning and attitudes. *Journal of Research in Science Teaching, 34*(5), 467–489.

Falconer, K., Wyckoff, S., Joshua, M., & Sawada, D. (2001). *Effect of reformed courses in physics and physical science on student conceptual understanding*. Paper presented at the Annual Meeting of the National Association of Research in Science Teaching, St Louis.

Fan, X., & Geelan, D. R. (2013). Enhancing students' scientific literacy in science education using interactive simulations: A critical literature review. *Journal of Computers in Mathematics and Science Teaching, 32*(2), 125–171.

Fang, Z. (1996). A review of research on teacher beliefs and practices. *Educational Research, 38*(1), 47–65.

Fogarty, I., Geelan, D., & Mukherjee, M. (2012). Does teaching sequence matter when teaching high school chemistry with scientific visualizations? *Teaching Science, 58*(3), 19–23.

Fogleman, J., McNeill, K. L., & Krajcik, J. (2011). Examining the effect of teachers' adaptations of a middle school science inquiry-oriented curriculum unit on student learning. *Journal of Research in Science Teaching, 48*(2), 149–169.

Frederiksen, C., & Breuleux, A. (1988). Monitoring cognitive processing in semantically complex domains. In N. Frederiksen, R. Glaser, A. Lesgold, & M. Shafto (Eds.), *Diagnostic monitoring of skill and knowledge acquisition*. Hillsdale: Lawrence Erlbaum.

Geban, O., Askar, P., & Ozkan, I. (1992). Effects of computer-simulations and problem-solving approaches on high-school-students. *Journal of Educational Research, 86*(1), 5–10.

Geelan, D. R. (1997). Epistemological anarchy and the many forms of constructivism. *Science & Education, 6*(1–2), 15–28.

Geelan, D. R. (2012). Teacher explanation of physics concepts: A video study. *Research in Science Education, 43*, 1751–1762. doi:10.1007/s11165-012-9336-8.

Geelan, D. R. (2013). Linking integrated middle school science with literacy in Australian teacher education. In T. A. Ferrett, D. R. Geelan, W. M. Schlegel, & J. L. Stewart (Eds.), *Connected science: Strategies for integrative learning in science*. Bloomington: Indiana University Press.

Geelan, D. R., & Mukherjee, M. M. (2010, May 17–20). *Measuring the effectiveness of computer-based scientific visualisations for conceptual development in Australian chemistry classrooms*. Global Learn Asia Pacific 2010, Penang.

Geelan, D. R., Larochelle, M., & Lemke, J. L. (2002). The laws of science. In J. Wallace & W. Louden (Eds.), *Dilemmas of science teaching: Perspectives on problems of practice* (pp. 22–35). London/New York: RoutledgeFalmer.

Geelan, D., Mukherjee, M., & Martin, B. (2012). Developing key concepts in physics: Is it more effective to teach using scientific visualisations? *Teaching Science, 58*(2), 33–36.

Gilbert, J., & Boulter, C. (1998). Learning science through models and modeling. In B. Fraser & K. Tobin (Eds.), *International handbook of science education* (pp. 53–66). Dordrecht: Kluwer Academic.

Ginsburg, H. P., & Golbeck, S. L. (2004). Thoughts on the future of research on mathematics and science learning and education. *Early Childhood Research Quarterly, 19*(1), 190–200.

Gobert, J. D. (2000). A typology of models for plate tectonics: Inferential power and barriers to understanding. *International Journal of Science Education, 22*(9), 937–977.

Gobert, J. D. (2005). Leveraging technology and cognitive theory on visualization to promote students' science. In J. K. Gilbert (Ed.), *Visualization in science education* (Vol. 1, pp. 73–90). Dordrecht: Springer.

Gobert, J. D., & Clement, J. J. (1999). Effects of student-generated diagrams versus student-generated summaries on conceptual understanding of causal and dynamic knowledge in plate tectonics. *Journal of Research in Science Teaching, 36*(1), 39–53.

Heath, P. A. (1992). Organizing for STS teaching and learning: The doing of STS. *Theory Into Practice, 31*(1), 52–58.

Hodson, D. (1990). A critical look at practical work in school science. *School Science Review, 71*(256), 33–40.

Honey, M. A., & Hilton, M. (2010). *Learning science through computer games and simulations*. Washington, DC: The National Academies Press.

Jacobson, M. J. (2004). Cognitive visualizations and the design of learning technology. *International Journal of Learning Technology, 1*, 40–62.

Kali, Y., & Linn, M. C. (2007). Technology-enhanced support strategies for inquiry learning. In J. M. Spector, M. D. Merrill, J. van Merrienboer, & M. P. Driscoll (Eds.), *Handbook of research on educational communications and technology* (3rd ed.). New York: Routledge.

Ketelhut, D. J. (2007). The impact of student self-efficacy on scientific inquiry skills: An exploratory investigation in River City, a multi-user virtual environment. *Journal of Science Education and Technology, 16*(1), 99–111.

Kinzie, M. B., Strauss, R., & Foss, J. (1993). The effects of an interactive dissection simulation on the performance and achievement of high-school biology students. *Journal of Research in Science Teaching, 30*(8), 989–1000.

Kloos, H., Fisher, A., & Van Orden, G. C. (2010). Situated naïve physics: Task constraints decide what children know about density. *Journal of Experimental Psychology. General, 139*(4), 625–637.

Klopfer, E., Yoon, S., & Rivas, L. (2004). Comparative analysis of Palm and wearable computers for Participatory Simulations. *Journal of Computer Assisted Learning, 20*(5), 347–359.

Knight, R. D. (2004). *Five easy lessons, strategies for successful physics teaching*. San Francisco: Addison Wesley.

Krajcik, J., Blumenfeld, P., Marx, R., Bass, K., Fredricks, J., & Soloway, E. (1998). Inquiry in project-based science classrooms: Initial attempts by middle school students. *Journal of the Learning Sciences, 7*(3), 313–350.

Lee, H.-S., & Songer, N. B. (2003). Making authentic science accessible to students. *International Journal of Science Education, 25*(1), 1–26.

Lee, H.-S., Linn, M. C., Varma, K., & Liu, O. L. (2010). How do technology-enhanced inquiry science units impact classroom learning? *Journal of Research in Science Teaching, 47*(1), 71–90.

Lemke, J. L. (1990). *Talking science: Language, learning, and values*. Norwood: Ablex Publishing Corporation.

Linn, M. C., Clark, D., & Slotta, J. D. (2003). WISE design for knowledge integration. *Science Education, 87*(4), 517–538.

Loucks-Horsley, S., Hewson, P., Love, N., & Stiles, K. (1998). *Designing professional development for teachers of science and mathematics*. Thousand Oaks: Corwin Press.

Lowe, R. K. (1993). Constructing a mental representation from an abstract technical diagram. *Learning and Instruction, 3*(3), 157–179.

Mazur, E. (1997). *Peer instruction: A user's manual*. Upper Saddle River: Prentice-Hall.

McCloskey, M. (1983). Intuitive physics. *Scientific American, 248*(4), 122–130.

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

National Research Council (NRC). (2005). How students learn: Science in the classroom. J. D. Bransford & S. Donovan (Eds.). Washington, DC: National Academies Press.

Pajares, M. F. (1992). Teachers' beliefs and educational research. *Review of Educational Research, 62*(3), 307–332.

Palincsar, A. S. (1998). Keeping the metaphor of scaffolding fresh – A response to C. Addison Stone's "The metaphor of scaffolding: Its utility for the field of learning disabilities". *Journal of Learning Disabilities, 31*, 370–373.

Plowman, L., & Stephen, C. (2005). Children, play and computers in pre-school education. *British Journal of Educational Technology, 36*(2), 145–158.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211–227.

Quellmalz, E. S., Timms, M. J., & Schneider, S. A. (2009, October 6–7). *Assessment of student learning in science simulations and games.* Paper commissioned for the National Research Council Workshop on Gaming and Simulations, Washington, DC. http://www7.nationalacademies.org/bose/Schneider_Gaming_CommissionedPaper.pdf. Accessed 23 Mar 2010.

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. V., Kyza, E., Edelson, D., & Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. *The Journal of the Learning Sciences, 13*(3), 337–386.

Rapp, D. N. (2005). *Mental models: Theoretical issues for visualizations in science education* (Vol. 1). Dordrecht: Springer.

Raths, D. (2012, May). Are you ready for BYOD? *THE Journal, 39*(4), 29–32.

Reiser, B. J. (2004). Scaffolding complex learning: The mechanisms of structuring and problematizing student work. *Journal of the Learning Sciences, 13*(3), 273–304.

Rivers, R. H., & Vockell, E. (1987). Computer simulations to stimulate scientific problem solving. *Journal of Research in Science Teaching, 24*(5), 403–415.

Rosenbaum, E., Klopfer, E., & Perry, J. (2007). On location learning: Authentic applied science with networked augmented realities. *Journal of Science Education and Technology, 16*(1), 31–45.

Russell, J. W., & Kozma, R. B. (1994). 4M: CHEM – Multimedia and mental models in chemistry. *Journal of Chemical Education, 71*(8), 669.

Sandoval, W. A. (2003). Conceptual and epistemic aspects of students' scientific explanations. *Journal of the Learning Sciences, 12*(1), 5–51.

Sandoval, W. A., & Reiser, B. J. (2004). Explanation-driven inquiry: Integrating conceptual and epistemic scaffolds for scientific inquiry. *Science Education, 88*(3), 345–372.

Schlager, M., & Fusco, J. (2004). Teacher professional development, technology, and communities of practice: Are we putting the cart before the horse? In S. Barab, R. Kling, & J. Gray (Eds.), *Designing for virtual communities in the service of learning*. Cambridge, UK: Cambridge University Press.

Slotta, J. D. (2004). The web-based inquiry science environment (WISE): Scaffolding knowledge integration in the science classroom. In M. C. Linn, P. Bell, & E. Davis (Eds.), *Internet environments for science education* (pp. 203–232). Mahwah: LEA.

Smetana, L. K., & Bell, R. L. (2011). Computer simulations to support science instruction and learning: A critical review of the literature. *International Journal of Science Education, 1–34*, 1337–1370. doi:10.1080/09500693.2011.605182.

Songer, N. B. (1996). Exploring learning opportunities in coordinated network-enhanced classrooms: A case of kids as global scientists. *The Journal of the Learning Sciences, 5*(4), 297–328.

Songer, N. B., Lee, H. S., & Kam, R. (2002). Technology-rich inquiry science in urban classrooms: What are the barriers to inquiry pedagogy? *Journal of Research in Science Teaching, 39*(2), 128–150.

Squire, K. D., DeVane, B., & Durga, S. (2008). Designing centers of expertise for academic learning through video games. *Theory Into Practice, 47*(3), 240–251.

Stieff, M., Bateman, R. C., Jr., & Uttal, D. H. (2005). Teaching and learning with three-dimensional representations. In J. K. Gilbert (Ed.), *Visualization in science education* (Vol. 1, pp. 93–120). Dordrecht: Springer.

Stone, C. A. (1998). The metaphor of scaffolding: Its utility for the field of learning disabilities. *Journal of Learning Disabilities, 31*, 344–364.

Tippins, D., & Kittleson, J. (2007). Considering young children's production of science: The tensions associated with processes, uncertainty, and authority. *Cultural Studies of Science Education, 2*(4), 816–822.

Varma, K., Husic, F., & Linn, M. C. (2008). Targeted support for using technology-enhanced science inquiry modules. *Journal of Science Education and Technology, 17*(4), 341–356.

White, R. T., & Gunstone, R. F. (1992). *Probing understanding*. Great Britain: Falmer Press.

Wilhelm, J., Wilhelm, P., & Boas, E. (2009). *Inquiring minds learn to read and write: A guide for using inquiry*. Oakville: Rubicon.

Wood, D., Bruner, J., & Ross, G. (1976). The role of tutoring in problem-solving. *Journal of Child Psychology and Psychiatry, 17*(2), 89–100.

Yager, R. E. (1996). History of science/technology/society as reform in the United States. In R. E. Yager (Ed.), *Science/technology/society as reform in science education* (pp. 3–15). Albany: State University of New York Press.

Zavala, G., Alarcón, H., & Benegas, J. (2007). Innovative training of in-service teachers for active learning: A short teacher development course based on physics education research. *Journal of Science Teacher Education, 18*(4), 559–572.

Zietsman, A. I., & Hewson, P. W. (1986). Effect of instruction using microcomputer simulations and conceptual change strategies on science learning. *Journal of Research in Science Teaching, 23*(1), 27–39.

Chapter 12
Transformed Instruction: Teaching in a Student-Generated Representations Learning Environment

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Abstract This chapter presents a novel way of approaching science education through activities involving Student-Generated visual Representations (SGR), and examines the role of the teacher in leading such instructional approach. We conducted a 4-week study in a sixth grade classroom (31 students) focusing on the topic of energy transformation. We designed an instructional unit involving activities of SGR that include: the generation of visual representations by students that describe energy transformations in various phenomena, small group negotiations and co-constructions of representations, class discussions on scientific principles centered around a selection of students' representations, and class discussions aiming to develop a set of criteria for evaluating representations. We demonstrate how aspects of such instructional design give rise to progressive activity structures, authentic forms of dialogue, and original ways for students to be explicit about their own ideas, and express themselves and their creativity. Nevertheless, meeting these opportunities requires a significant transformation of the teacher's role in the classroom, which may profoundly challenge her epistemological beliefs. We argue that this instructional approach, with the appropriate guidance, can serve as a springboard for such deep transformation of teacher epistemological beliefs, which in turn support the emergence of new instructional practices.

Keywords Student-generated representations • Energy • Pedagogy • Instructional design • Evaluation • Intuitive knowledge resources • Authentic dialogue • Process approach • Transformation of teachers' role • Critiquing • Meta representational competence

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12.1 Introduction

> Tuesday morning. Rain is pouring outside. The classroom is bustling with students' voices, and loud arguments. The students are sitting in groups. In fact, some of them are standing, moving restlessly. It is science class and the students are learning about energy transformation. They are experimenting with balls tossed upwards, trying to figure out the types of energies playing out in the situation, and the transformations that are taking place from Kinetic Energy to Potential Energy and vice versa. While playing with the balls, each pair tries to represent the energy transformations in the situation in drawings. It is never easy to agree on one way to represent the energy types and their quantities. When students only talk (verbally) about these things they tend to wave their hands and overlook details, but when they produce visual representations on a paper, making their ideas public and subject to careful inspection and monitoring, details become the center of arguments and disagreements. Moreover, there are multiple ways to represent energy transformations that usually involve creative thinking and self-expression. Students negotiate their ideas and try to convince each other, and this may become quite loud sometimes. These all lead to excitement and agitation in the classroom during this morning.
>
> In the midst of this lively turmoil, there is the teacher. She doesn't try to impose any order on the classroom, as she recognizes that the students are on-task. She is wandering from one pair to another, while other pairs of students reach for her and proudly ask her to look at their creations.
>
> By the end of the session, a new experience for her in an experimental unit, the teacher expresses her mixed feelings: "It is very exciting to see the students' bright eyes, their intensive engagement and enthusiasm. I am especially moved by the level of engagement of those students who never participate in Science classes. Yet, I'm overwhelmed. I have a feeling of losing control. I feel that they all need me, and they all want to share with me their creative work and I can't be there for all of them. Besides, I can see many scientific mistakes they are making in their drawings. It is right there at my face, drawn clearly on paper which is really hard to ignore. I want to work with them on the scientific accuracies, but I can't reach them all at once."

This was an actual situation in our recent experimental unit centered on activities of Student-Generated Representations (SGR). It was the third class in a six double lesson unit we have designed for a full sized sixth grade classroom, after piloting this unit twice with a smaller group of students ($n = 10$) during the summer vacation, and prior to that, with pairs of students.

We designed this unit so that the learning of scientific concepts and phenomena are organized around visual representations. These visual representations are not pre-designed by the teacher or the curriculum designer, but are produced and elaborated by the students, as a means for developing and deepening their understanding.

As demonstrated in the above narrative, we had a significant experience in this classroom. On the one hand, our invitation for students to design their own representations, drawing on their existing knowledge resources and their sources of creativity, stimulated students' engagement and involvement, including those who hardly take active part in Science classes. It also created for the students the opportunity to engage in a profound process of knowledge development. On the other hand, the same stimulating activity for the students introduced some challenges for the teacher. It was hard to witness explicit mistakes on paper, without being able to work on these mistakes with the students at the moment they become visible. This stands in contrast to the situation of a traditional Science class, where the teacher's voice is more dominant and she has more control over what is being said and become shared by the classroom. In such situations students obviously have many mistakes and pre-conceptions, but most of them are hidden in their minds. Moreover, the same scientific ideas were expressed by a rich diversity of different forms of representations. It requires developing standards and criteria shared by the classroom, for judging the quality and functionality of visual representations.

Harvesting the fruits of such learning environment requires taking a certain instructional approach, embracing the following set of principles:

- **Encouraging students to build on their intuitive knowledge resources** – even if not scientifically accurate, these resources, are productive seeds of students' scientific understanding, and thus should be operated on, expressed and communicated, towards a more sophisticated and scientific knowledge.
- **Engaging students in authentic dialogue** – an authentic dialogue enables students to express their ideas, to present their insights, to ask questions and to argue about different interpretations in an open, and non-judgmental discussion.
- **Adopting a process approach** – The first attempt to generate a representation is usually basic and crude. The significant development in students' understanding occurs through a process of elaboration and discussion of their ideas around their representations. Students should be given the opportunity to develop their explanations and understanding from basic and intuitive to more nuanced ones.
- **Arranging various types of interactions** – The environment should be rich in interactions and combine moments of individual thinking and representing, small-group collaborative work, instructor and small-group interaction, and whole class discussions.
- **Encouraging original invention and self-expression** – Students should be encouraged to create original means of expressing their ideas visually. Through the process of developing more sophisticated representations, students can develop their competencies of creating and inventing visual representations that help them and others understand difficult phenomena.

Adhering to these principles requires a transformation in the role of the teacher. The teacher should provide a wide-ranging space for students for pursuing their own ideas and expressing these ideas in unique ways. This requires establishing a safe, non-judgmental environment and discourse in the classroom. The numerous opportunities provided for students to interact with others would be genuine only if the teacher establishes the legitimacy of students as trustworthy sources for learning. Patience and trust in the long process are required as well.

These transformations cannot be artificial or done only on the surface-behavioral level. An authentic and profound change in teacher practices should follow a deep change in the teacher's epistemological beliefs.

12.2 Theoretical Background

12.2.1 Student-Generated Representations in the Classroom

Promoting visual means as forms of thinking and expression for students is particularly important given the tendency of increasing range of innovative and sophisticated visualizations that enhance various types of information in many fields (e.g., Tufte 2001). Moreover, scientists use representations in their practice to promote their understanding, to think with in order to make scientific progress, and to communicate with other scientists (Latour 1986; Lynch and Woolgar 1990; Ochs et al. 1994). Yet, examining school practices reveals that most modes of expressions are verbal and textual, while students' opportunities to express their ideas visually are fairly limited.

Gilbert (2008) emphasizes the importance of fluent performance in visualization involving the ability to acquire, monitor, integrate, and extend, learning from representations. He calls this fluent performance in visualization: meta-visualization. An important part of this fluency is the ability to design new models (Justi and Gilbert 2003).

DiSessa et al. (1991) studied students' meta-representational competencies. They showed that elementary school students have many competencies for creating, critiquing and inventing new representations. Developing these competencies, they suggest, is important in enhancing students' representational innovation, as well as deepening their understanding of any kind of representation (diSessa 2004). Other researchers emphasized students' original representational inventions for expressing their own ideas (Bamberger 2007; Hall 1990; Enyedy 2005; Danish and Enyedy 2007).

Focusing teaching and learning around student-generated representations creates new possibilities for classroom interaction. External representations have affordances that make them good facilitators for communicative activities and collaborative knowledge construction. Goodwin (2003) emphasizes the notion of *public field*, on which visible, and meaningful action can be performed (e.g., gestures and talk referencing the representations). A shared orientation to visible action in a publicly observable space is crucial to instruction as well as to a collaborative activity. Healey (2006) argues that visual representations support interaction processes due to their *persistence*, in contrast to the transient nature of verbal exchanges. The persistence characteristic shapes practices of referencing back, reintroduction of ideas, revisions etc. These affordances support important scientific practices (Latour 1986; Lynch and Woolgar 1990; Ochs et al. 1994), and potentially science classroom practices.

To gain full potential from these classroom practices, the teacher should enable such processes to happen and flow. An important aspect of the teacher's approach as enabling such processes is her ability to facilitate a dialogic discourse with her students through various types of interactions.

12.2.2 Dialogic Discourse

Peled and Bloom-Kolke (1997) define a dialogue as a situation where authentic questions are asked and authentic answers are given in order to form a discursive text that is meaningful for all participants.

An Authentic dialogue enables students to express their ideas, to present their insights, to ask questions, to make comments and to argue about different interpretations. A good dialogue discourse enables students to clarify meanings and express their real thoughts, instead of expressing ideas that they think their teacher expect them to learn (Yechiely and Nussbaum 1998).

There is an agreement about the necessity of a dialogue in the educational process, although, some types of dialogue are more meaningful for learning than others. Peled and Bloom-Kolke (1997) recognized four types of dialogic discourse that can take place in the classroom:

1. A monologue in a dialogue disguise
2. A supposedly dialogue
3. A Socratic dialogue
4. An authentic dialogue

Studies have shown that a *monologue in a dialogue disguise* and a *supposedly dialogue* are the most common types of dialogue in class**.** The former is characterized by a dominant teacher who asks short and inconclusive questions, where students are expected to recite details they have heard in class before.

An *authentic dialogue* is characterized by the teacher's attempt to conduct a genuine conversation based on a real interest in students' ideas. This situation is characterized by the teacher's ability to delay the "teaching control", and to really listen to the students. In so doing, the dialogue can start at one point and end up in another, unpredictably. In both the Socratic dialogue and the authentic dialogue the students are very active and involved (Peled and Bloom-Kolke 1997).

A *dialogic teaching*, according to Alexander (2004), should satisfy the following five criteria:

1. Collectiveness – teachers and students cope with the learning task together.
2. Reciprocity – teachers and students listen to each other, share ideas and weigh alternative points of view.
3. Support – students are liberated to formulate their ideas, free of embarrassment of giving "wrong" answers.
4. Accumulation – teachers and students base their ideas on each other, and connect them together to form coherent paths of thoughts and inquiry.
5. Intentionality – teachers plan and navigate the class discourse in light of specific educational goals.

Nave (2009) claims that a meaningful dialogue may be blocked due to the teacher, her approach and her epistemological beliefs. This leads us directly to the last part of this theoretical review.

12.2.3 Teachers' Epistemological Beliefs

Conducting a dialogic discourse of the type we would like to encourage (an authentic discourse), and a dialogic teaching in general, is not only a matter of a technique or a skill that one should acquire, but a special approach that is tied to the teacher's epistemological beliefs.

Research on epistemological beliefs has made an important contribution to education, in identifying epistemology as a category of informal knowledge that may play a role in both teachers', and students' learning processes (Hammer and Elby 2002). Within the last 15 years, understanding teacher beliefs has become a priority for educational researchers (Luft and Roehrig 2007). Epistemological beliefs range between positivist beliefs and relativist beliefs. Relativists perceive the learning process as dynamic, characterized by thought flexibility, meaning and authenticity. Students are encouraged to doubt, to ask questions and to examine the world from various perspectives. Teachers with positivist beliefs view their teaching role as active compared to the student who is viewed as passive, while teachers with relativists world view believe that each learner constructs unique knowledge base that is different from each other but equivalent to others (Olafson and Schraw 2006).

Another important epistemological dispute is between two learning approaches: the empiricist and the constructivist approaches (Yoed and Levin 2007). Following the constructivist approach, each student should organize and construct her knowledge of the world on her own, based on her tendencies and the resources she has and based on her cognitive structures. At the end, the student should choose, filter, process, interpret and organize her knowledge on her own. Children don't get ideas, they create ideas. The teacher's role is to arrange a learning environment for the child and to create situations in which the child could interpret, discover and construct her understanding of the world. In order to teach in this approach, the teacher must have the appropriate epistemological beliefs that allow him to enable the students to be active in these ways, and to deeply understand that the teacher cannot *do the work for the student*, but only accompany her in this journey.

There is a great importance to the epistemological beliefs when the teacher aims to adopt constructivist teaching practices (Yoed and Levin 2007). For example, a teacher that holds the belief that the only knowledge source is the pedagogical authority, or the textbook written by experts, may not see the reason to develop an authentic dialogue with his students. If he doesn't view the students as a knowledge source, he may avoid asking thinking questions, encouraging criticism and expressing personal opinions, and will be satisfied with recitation and rehearsals of information provided by him. Conversely, a *dialogic teacher* (Freire and Shor 1987) stands out in her advanced epistemological beliefs, and doesn't behave as the owner of knowledge. She encourages her students to develop critical insight and independent thinking and in that re-creates new knowledge opportunities.

12.3 The Learning Environment – Learning Energy Transformation Through Student-Generated Representations

We conducted the experimental unit in January 2012. The unit lasted 6 weeks, 2 h a week. The students were in sixth grade in an elementary school at the center of Israel. Thirty-one students participated, (17 boys and 14 girls), 3 of them are classified as having special learning difficulties.

The structure of the learning environment is displayed in Fig. 12.1. In general, the learning environment had the following main components:

1. A series of introductory activities to the topic.
2. An activity of student-generated representation, where students represent energy transformation of a specific experimented phenomenon.
3. A series of discussions and elaborations of the representations in various settings (working in pairs, group discussion, class discussion).
4. Class discussions aiming to develop a set of criteria for evaluating representations.

The teacher took the lead on the classroom activities and discussions while the researcher also had active role in talking to students as they were working in groups, or in participating in class discussions.

Data were collected using various tools: (1) Field notes taken by the researcher who was present in all classes; (2) Video records of all class discussions. Video records were focusing only on the teacher. (3) Students' representations in different phases, including photos of representations drawn on the board.

For this chapter, two episodes were analyzed, taken from lesson 3 and 4. These episodes emphasize the unique features of the learning environment and the role of the teacher in facilitating the leaning activities.

12.4 Analysis

12.4.1 Episode 1: Students Generate Representations of Energy Transformations

Lesson 3 began with a brief discussion on different forms of energy and energy transformations, as a summary of the previous lesson. At 3:20 min into the lesson, the teacher demonstrates a phenomenon of a tossing ball to the classroom. She holds in her hand a tennis ball and asks the students to watch the ball when she throws it up in the air, and then catches it when it falls down. She then says:

> I would like you to tell me what kinds of energy play a role in this phenomenon.

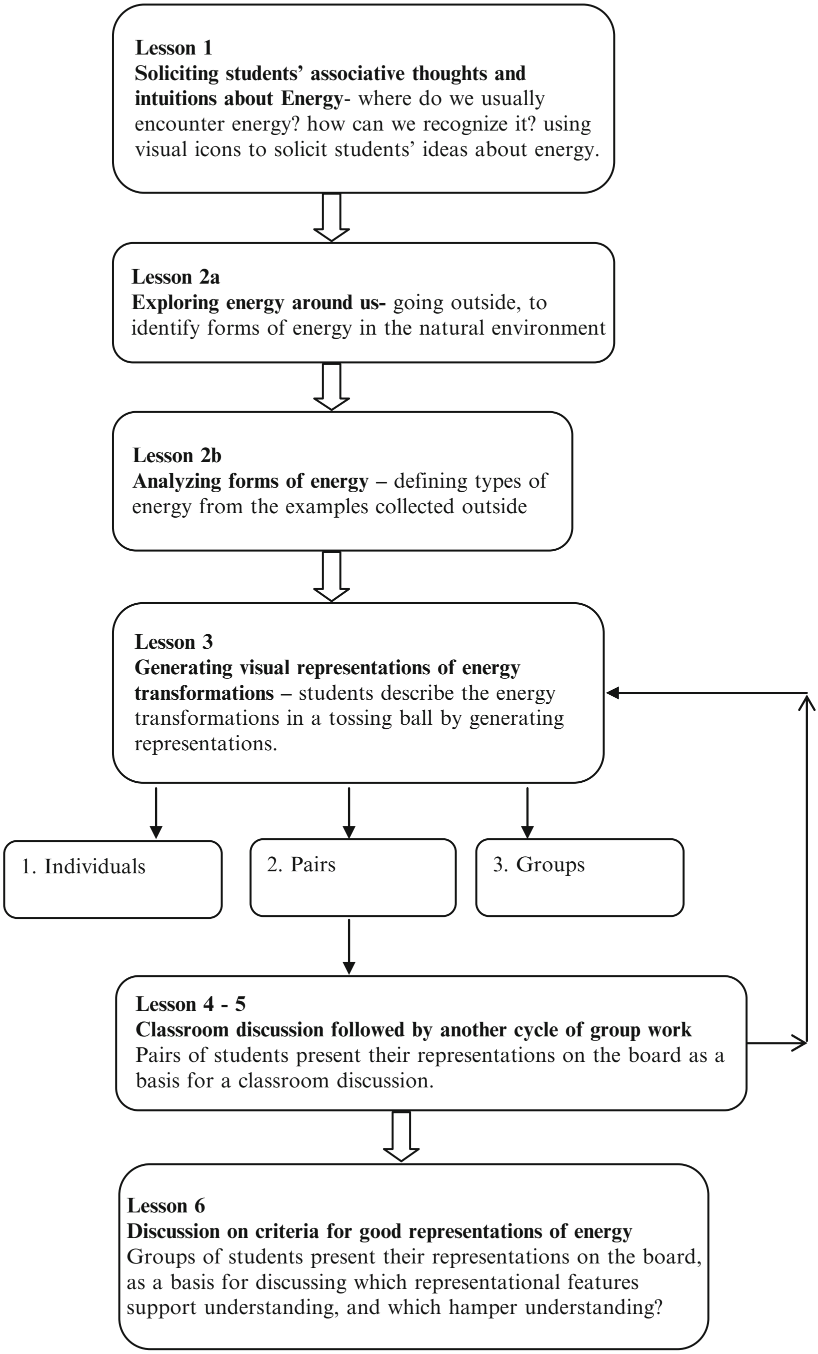

Fig. 12.1 The instructional unit on energy transformations

The students say the kinds of energy they infer from what they see in the ball's motion. The teacher briefly discusses their answers, clarifying some of the answers and asks to explain the reasons behind others.

At 5:44 min the teacher introduces the task:

> In the first phase, I would like you now, each on your own, to draw a drawing that explains what we have been just discussing, the kinds of energy, and energy transformations. Pay less attention to the drawing of the situation itself, although you can do that too, but please emphasize more the kinds of energy and energy transformations.

The researcher added:

> You know that we cannot really see energy with our eyes, so when we draw "energy" we can't draw the real thing, but we invent a way to represent energy so we can think about it and see it, and we cannot copy it from reality, we invent a way to represent it

Students ask some more clarification questions and then they are asked to generate their individual drawing for 15 min (at 8:53 min).

The students draw by themselves representations of the energy transformations of the tossing ball. After a few moments, the teacher provides tennis balls to experiment with. The teacher and the researcher wonder around, look at students' representations and ask them questions about their choices. Students are eager to show their drawings, to ask if they are "right," as well as to brag about their creative and unique drawings. Wondering around the students also raised some points for the teacher that she could than raise with the students in the class discussion in order to refine her instructions.

After students drew their individual representations the teacher called their attention. She made some clarifications and then provided instructions for the second phase of the activity:

> Now, work in pairs, and like you did with us (the teacher and the researcher) before when you explained to us, do the same with a peer: explain to him/her your drawing, and then talk about it and try to create together a shared drawing that explain the phenomenon as best as you can

The students discussed their drawings and the phenomenon and generated new representations, this time, shared representation. Figures 12.2–12.6 are selections of students' representations.

12.4.2 *Some Observations and Reflections on This Episode*

This lesson highlights the challenge and the promise of such an instructional approach. Each of the observation we will highlight here has these two faces, pointing to a difficulty of students or of the teacher, but also to some powerful new opportunities.

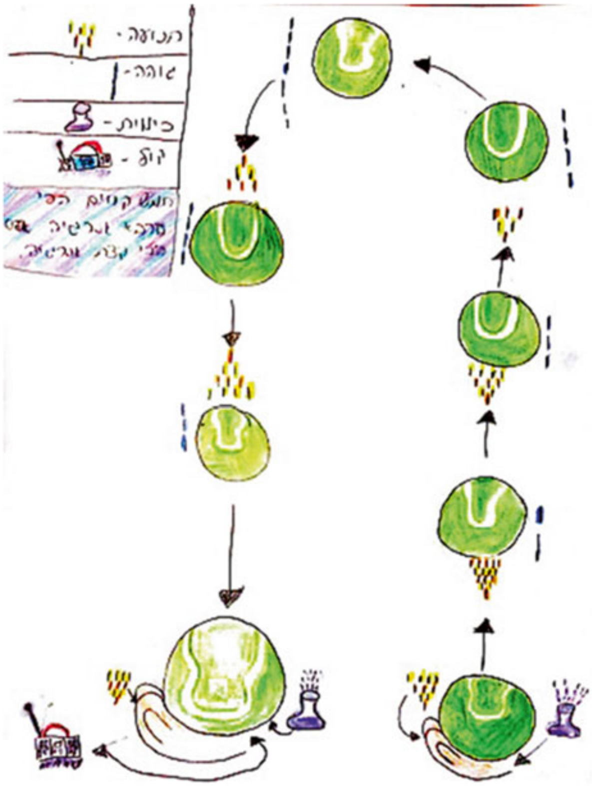

Fig. 12.2 Kinetic energy is represented by the quantities of *small lines* arranged as a triangle, potential energy is represented by *vertical lines*, chemical energy is represented by a *laboratory container*

12.4.2.1 This Is All New to the Students

It is obvious, that such an approach is new to the students. Students were looking almost obsessively for the teacher's acknowledgement. Their seeking for her acknowledgement is a result of two main reasons. (1) They are still looking for the authority to tell them whether they are right or wrong. (2) They put efforts in their drawing, and expressed themselves in creative ways so that their drawing is unique. A sense of ownership and pride make them eager to show their teacher their creative work. Interestingly, what might seem intimidating and risky for some students, is a new fresh opportunity for others. It was striking to notice the most silent students as well as students with special difficulties finding their way to express themselves and bring themselves forward. They were able to reveal new sides of their selves that they usually are not called upon. This seemed to contribute dramatically (from what we have seen) to their self-esteem.

12.4.2.2 Rich Variety of Representations

The teacher faces a rich variety of students' drawing. No one's drawing is similar to another (see, for example, Figs. 12.2, 12.3, 12.4, 12.5 and 12.6). It is difficult to interpret so many different representational ideas on the spot. The teacher needs to

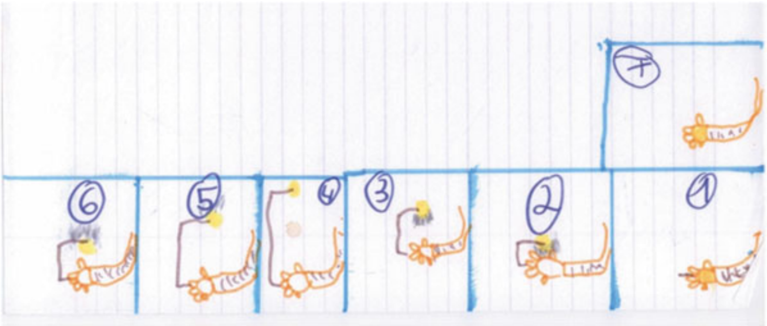

Fig. 12.3 Potential energy is represented by the length of the line, and kinetic energy by the size of the “radiance” around the ball

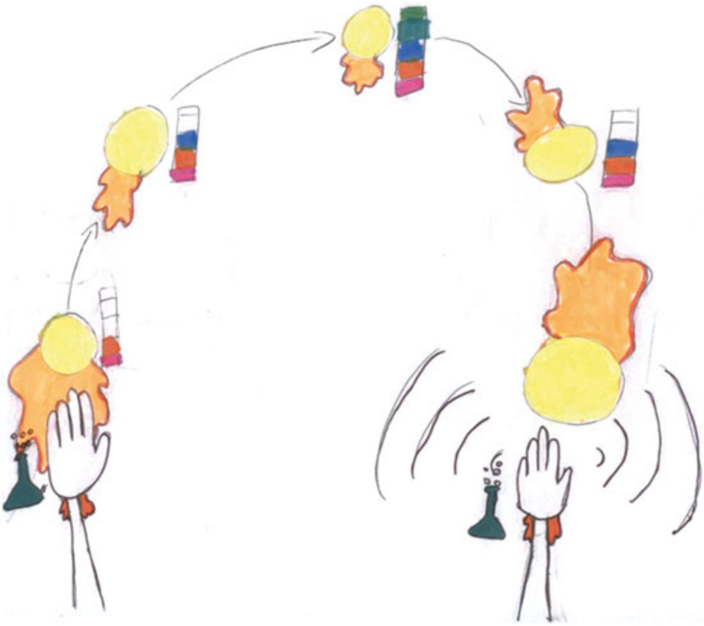

Fig. 12.4 Energy types are represented by specific shapes. Sizes of these shapes represent the quantity of this type of energy

practice a fresh approach of listening to students and their ideas in order to appreciate their drawing. Some of the drawings may be very hard to interpret and require a detailed examination and discussion, such as the drawing in Fig. 12.6. On the other hand, such richness enables the teacher to open up interesting and meaningful discussions on different ways of representing energy types, which by all means can enhance their thinking about the concept of energy, and energy transformations. Beyond that, students’ excitement and burst of creativity can be a rewarding and gratifying experience for the teacher, no matter how much efforts she puts in sustaining such a learning environment.

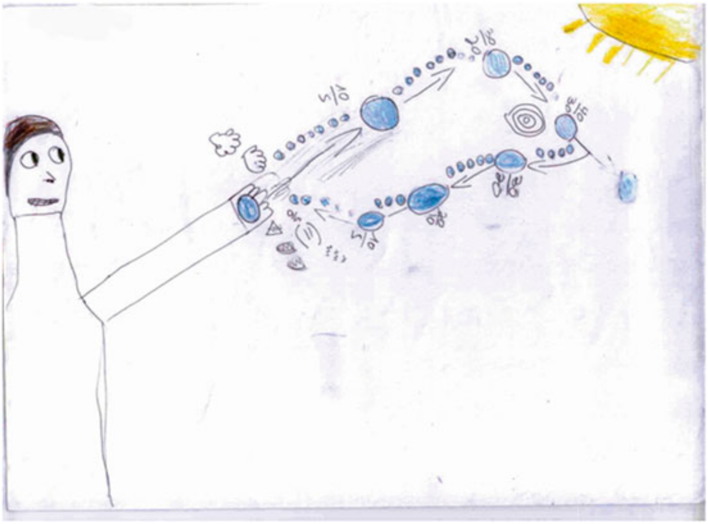

Fig. 12.5 Kinetic and potential energies are represented by numbers

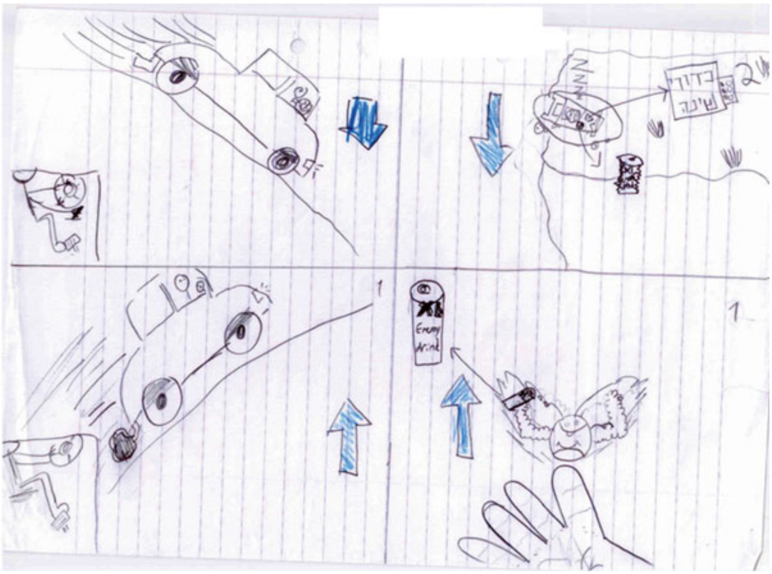

Fig. 12.6 A creative but hard to interpret representation. Each step in the motion of the ball is represented by a scene

12.4.2.3 Students' Naïve Ideas

When students are asked to explain and provide their own ideas and understanding, they reveal their naïve understanding which may be different from normative scientific understanding. On the one hand, these naïve understandings are surfaced by the visual nature of the drawings – they are right there, exposed, drawn on a paper, with vivid colors and shapes. The teacher may feel overwhelmed by the amount of work needed to bring the students to a normative understanding. On the other hand, this is a great opportunity to actually be able to see what is usually buried in students' minds. It is also important to note that the students receive several opportunities to improve their drawing (and their understanding). They first draw individually, and then draw together with a peer where some conceptual issues may be already resolved. Later on (in the next episode) there is a discussion around a few of the drawings where scientific issues are negotiated together and resolved, and then the students draw individually again, now with an improved understanding.

12.4.2.4 Messy Environment

Lessons in this approach are messy and look to the outsider a bit disordered. The class is noisy, and students may walk around. The pace seems to be slower and is dictated by the class, less by the teacher. The teacher indeed orchestrates this messy activity, and decides when to stop an activity and move to the next, but the students have an important role in dictating the pace of the lesson. Using this approach takes time, patience, and tolerance towards noise and disorder. But the benefit is a cheerful and vivid affair in the classroom, meaningful learning and unexpected and therefore interesting directions for learning and discussions.

12.4.3 Episode 2 – Students' Visual Representations as the Center of Class Discussion

This episode took place at lesson 4, after pairs of students produced representations of the tossing ball. Three pairs of students volunteered to present their drawings on the board, and these drawings became the center of the class discussion.

The drawings, different from one another, reflect some unique and novel ideas:

1. Ohad and Chemi drew an icon for each type of energy. Kinetic energy = airplane, potential energy (height) = kite. The sizes of the icons represent the quantity of each type of energy. For example: a small airplane represents a small amount of kinetic energy (Fig. 12.7).
2. Ilan and Shani use colors to represent different types of energies: kinetic energy in blue, potential energy in red. The quantities of energy in each stage are represented in a pie shape colored in proportion to each energy quantity.
3. Mor and Meir use numbers to represent the quantities of energy at each stage.

The teacher invited the students to comment and ask questions about the drawings. Many fingers were raised. The first were clarification questions – students wanted to understand why something is drawn the way it is. For example, Maya asked Ilan and Shani about their drawing (Fig. 12.8):

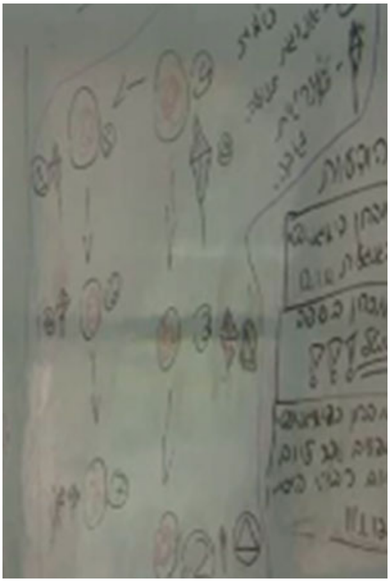

Fig. 12.7 Ohad and Chemi's representation

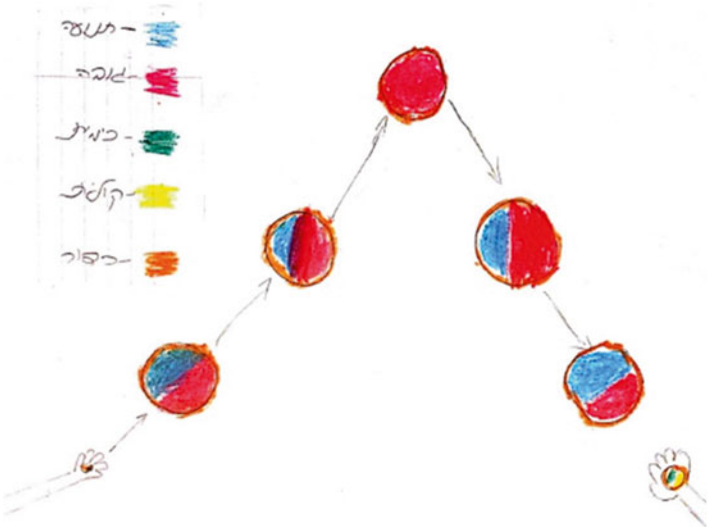

Fig. 12.8 Ilan and Shani's representation

Maya:	I didn't get it. The ball on the other side, when it falls down, why it is colored yellow, and also colored…
Mor:	look up at the legend
Teacher:	does anybody understand and want to explain? Maya asks about the yellow…
Sivan:	in the first hand there is green – Chemical (energy), it jumps and it has height and motion.
Teacher:	how do you know it is height and motion?
Sivan:	Because it says in the legend. Motion is blue and height is red. And then there is only height and when it goes down the height and motion and then down it is again in the hand – chemical (energy), and it has sound energy, which is yellow

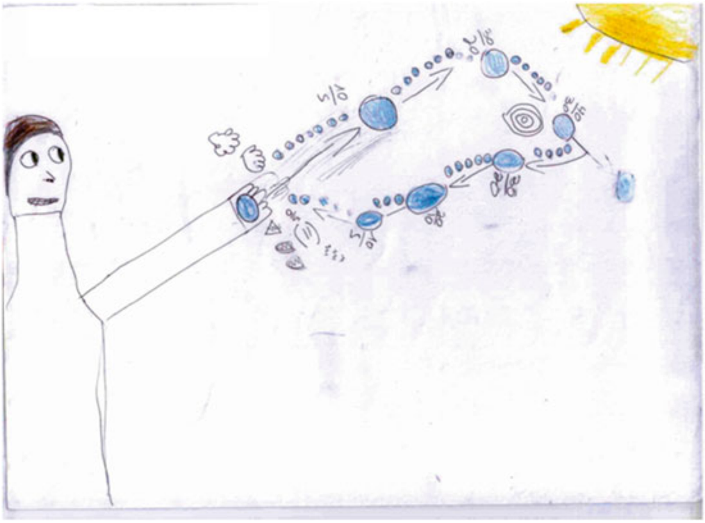

Fig. 12.9 Mor and Meir representation

In this example, Maya asks about an aspect in the drawing she didn't understand. Her question is followed by a collective effort to make sense of the representation. One student, Mor, mentions the legend as relevant to the use of colors in the drawing. The other student, Sivan, provides her interpretation to the representation. The teacher asks Sivan on what accounts she makes her interpretation, and Sivan acknowledges again the legend.

This dynamic continues in the next discussion, and even gets enhanced. The teacher shifts the discussion to the third drawing of Mor and Meir (Fig. 12.9).

Teacher:	Who can refer to Mor and Meir's drawing? Who understood something and can make a comment? Neta?
Neta:	These fractions are like, this is like size, say… but I don't really know what they are, say, height or motion?
Teacher:	What do you think they represent, these numbers, these fractions?
Neta:	I don't know, height
Teacher:	height?
Neta:	Yes, because I think the motion is the small little circles
Teacher:	What can be understood from the fraction in every stage? Look at them, Does the number get smaller or bigger?
A student:	It gets smaller, because at the beginning there are two whole numbers and then…

The teacher solicits comments related to the third pair's drawing. This drawing seems harder to interpret. Neta makes an attempt to interpret what the numbers are – she thinks these are fractions because the way they are written, for example: 10/5. She assumes that the numbers represent somehow potential energy (height), and the little circles represent kinetic energy.

The teacher, who doesn't actually know how Mor and Meir chose to represent energy transformation, joins Neta in her effort to make sense and encourages her to look at the fraction and see if they get smaller or bigger.

At this point, the teacher invites Mor, one of the students that drew the representation, to come to the board and show when does the motion actually start. Gradually, as the next excerpt demonstrates, they realize that the idea behind the representation is very different than what they have thought.

Teacher:	Mor, go to the board and show where does it start
	Mor goes to the board: it is like we start to look here (points to the beginning), it is like the height: 10, 20, 30
Neta:	So, how is it that the height is the highest at the beginning?
Mor:	No. Here it is the highest, it is Kilometer, not fraction, it is like a ruler
Teacher:	Show us the beginning. Show her where the beginning is.
Mor:	Here, it is like a ruler…only that… this is how my ruler looks like
Teacher:	But why, in fact you wrote a fraction? 10/5
Mor:	No, this is like the height: say 5 cm, 10 cm, it grows.
A student:	Why here is 10/5 and here it is 20/10
Mor:	It is not fractions, it is centimeters. [A student: it is height]
Researcher:	Here it rises from 5 to 10, is this what you are saying? and there from 10 to 20?
Teacher:	Ah, OK
Mor:	Yes, from here 10 to 20, 20 to 30, and then it starts to fall.
Researcher:	Ah…
Teacher:	I got it
Mor:	and the circles are the motion, and this is the chemical energy, and this is the sound energy… like in TV.
Researcher:	and the circles are the motion? Is that kinetic energy?
Mor:	Here the motion is greater, and here it is smaller. A little bit smaller, it gets smaller. Here there is one circle, here two, three, four…

Mor comes to the board and explains the way they have represented height, in order to infer potential energy. He reacts to several students' attempts to interpret the representation incorrectly, including the teacher. He keeps saying that the numbers do not represent fractions but height – like in a ruler (kilometers, centimeters). At last, he was able to get his explanation through, correcting the students and the teacher's misinterpretation of their representations.

12.4.4 Some Observations and Reflections on This Episode

This episode emphasizes two main ideas: the central role of representations as a public field supporting a productive discussion, and the opportunity for conducting an authentic dialogue.

1. The representations serve as a public field

In this episode, the discussion is organized around several representations drawn on the whiteboard. It is a good example how external representations can facilitate communicative activities and collaborative knowledge construction. The students can easily refer to their friends' ideas and provide feedback and immediate repair.

This creates a vivid discussion, and the students are very active explaining themselves and defend their arguments.

The drawings are presented on the board, a public field (Goodwin 2003) seen by everybody in the classroom, and are subjects for scrutiny. Students, both the ones who ask questions, and the creators of the representations, perform meaningful actions (make gestures, make references to the representations as they speak) that are visible to everybody. This shared orientation to visible action in a publicly observable field enables participants to ask specific questions, to hold each other accountable for what is been said or drawn, and facilitate the discussion.

2. Conducting an authentic dialogue

This episode demonstrates some important aspects of an authentic dialogue (Peled and Bloom-Kolke 1997), such as conducting a genuine conversation based on students' ideas, delaying "teaching control", and listening to the students.

In the excerpts above, all students are invited to make comments and to ask questions, and at the same time are also invited to provide answers to their friends' questions, and to help each other make sense. The teacher doesn't have ownership on the knowledge. She doesn't provide any clarifications on the drawings. In fact, she is in a challenging position where she may not even have an available interpretation of students' representations at the moment, and she makes efforts to make sense with the students. Thus, she must make a real and honest effort to understand the students' ideas as they unfold. The teacher still has an important role in facilitating the social dynamic and knowledge construction. She solicits explanations from students, highlight ideas, to help other students pay attention to them (e.g., "how do you know it is height and motion?")

The way the teacher situates herself in the room is also indicative. She stands at the side, looking at the board with all the other students. Moreover, in contrast to the common classroom situation where the teacher has the exclusive right for using the whiteboard, here students use the board quite naturally and liberally.

12.5 Discussion

Shor and Freire (1987) describe the essence of a dialogue between a teacher and a student:

> Paulo: Yes, dialogue is a challenge to existing domination. Also, with such a way of understanding dialogue, the object to be known is *not* an exclusive possession of *one* of the subjects doing the knowing, one of the people in the dialogue. In our case of education, knowledge of the object to be known is not the sole possession of the teacher, who gives knowledge to the students in a gracious gesture. Instead of this cordial gift of information to students, the object to be known mediates the two cognitive subjects. In other words, the object to be known is put on the table *between* the two subjects of knowing. They meet around it and through it for mutual inquiry…What is dialogue in this way of knowing? Precisely this connection, this epistemological relation.

The use of the student-generated representations as an anchor of the class discourse and sense making activity generated some unique opportunities for authentic dialogue of this sort.

First, centering the discourse around a physical-visual representation enables students to hold each other accountable for what is drawn, generate discussions that are grounded in something concrete and visible, shared by everybody in the room, ask questions, and make specific references to aspects of the drawing. These lead to rich and engaging discussions, in which the teacher does not have any privileged status over the students. She asks questions, honestly attempting to understand students' ideas, free of judgmental attitude. Everybody in the classroom can be engaged in this kind of activity equally, and make a good effort to interpret and make sense of the situation in front of them.

The fact that each student or a group of students generated a unique representation creates a sense of ownership along with a sense of competency. Each student is at least an expert in her own creation (for example, recall Mor's explanation of his representation). This sense of ownership and competency was remarkable with special education students. They felt empowered, and were encouraged to take active part in classroom discussions and to bring their ideas to the fore. Beyond the motivation and engagement that students may feel, this sense of ownership and competency creates an atmosphere of equality and legitimacy that are necessary for an authentic dialogue. This has to be accompanied by a non-judgmental atmosphere that the teacher should cultivate.

Coping with students' mistakes and misunderstandings is a challenge in this learning environment. The teacher has the responsibility to help her students develop normative understanding, but at the same time to respect and appreciate students' genuine ideas and discuss them. The challenge of teaching in such a constructivist learning environment is to find ways to facilitate productive discussions and activities leading to conceptual change.

Having a teaching experience in such an instructional unit can serve as a springboard for the transformation of epistemological beliefs, provided a supportive guidance. The teacher may notice the dramatic change in her students' patterns of engagement and motivation, the participation of students who usually are very silent, the wealth of ideas and representations, the burst of creativity and self-expression, and the promising potential in gaining access to students' ideas and ways of thinking about the topic. All these advantages may provide an impetus for making the effort and dealing with the challenges of such an environment, including the release of control, letting go of the privileged position and the authority, and the challenge of dealing with many new ideas and representations in the midst of a buzzing environment.

Adhering to such practices requires yet a deep transformation of the teacher's epistemological beliefs. A gradual transformation from an empiricist approach to a constructivist approach could be facilitated by a supportive guidance and a thorough reflection on the classroom experience. For example, the teacher should reflect and discuss the meaning of her exposure to students' ideas, their richness and variety. Specifically, what does it mean to her to be open to students' naïve ideas that are far from normative explanations? It is important to discuss constructivist ideas related to students' active construction of their knowledge based on this experience, compared to the common empiricist belief that the students "learn and know" the right scientific ideas when the teacher say and explain them clearly. Reflecting on the class discussion and students' group work can highlight the merits of the teacher's ability to discuss students' genuine ideas, and support their construction of knowledge. It is also inevitable for the teacher to realize and appreciate through this process the complexity of the teaching endeavor in facilitating such learning.

References

Alexander, R. J. (2004). *Towards dialogic teaching*. London: Dialogos.

Bamberger, J. (2007). Restructuring conceptual intuitions through invented notations: From path-making to map-making. In Teubal (Ed.), *The development of notational representations*. New York: Oxford University Press.

Danish, J. A., & Enyedy, N. (2007). Negotiated representational mediators: How young children decide what to include in their science representations. *Science Education, 91*(1), 1–35.

diSessa, A. A. (2004). Meta-representation: Native competence and targets for instruction. *Cognition and Instruction, 22*(3), 293–331.

diSessa, A. A., Hammer, D., Sherin, B., & Kolpakowski, T. (1991). Inventing graphing: Meta-representational expertise in children. *Journal of Mathematical Behavior, 10*, 117–160.

Enyedy, N. (2005). Inventing mapping: Creating cultural forms to solve collective problems. *Cognition and Instruction, 23*(4).

Freire, P., & Shor, I. (1987). *A pedagogy for liberation: Dialogues on transforming education*. South Hadley: Bergin and Garvey.

Gilbert, J. K. (2008). Visualization: An emergent field of practice and enquiry in science education. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 3–24). New York: Springer.

Goodwin, C. (2003). Pointing as situated practice. In S. Kita (Ed.), *Pointing: Where language, culture and cognition meet* (pp. 217–241). Mahwah: Lawrence Erlbaum.

Hall, R. P. (1990). *Making mathematics on paper: Constructing representations of stories about related linear functions*. Unpublished dissertation, University of California at Irvine.

Hammer, D., & Elby, A. (2002). On the form of a personal epistemology. In B. K. Hofer & P. R. Pintrich (Eds.), *Personal epistemology: The psychology of beliefs about knowledge and knowing* (pp. 169–190). Mahwah: Lawrence Erlbaum.

Healey, P. G. T. (2006). Drawing things together: Integrating modalities and co-ordinating understanding. In *Sixth IEEE International Conference on Advanced Learning Technologies ICALT'06* (pp. 1200–1201). Kerkrade.

Justi, R., & Gilbert, J. K. (2003). Teachers' views on the nature of models. *International Journal of Science Education, 25*(11), 1369–1386.

Latour, B. (1986). Visualization and cognition: Thinking with eyes and hands. *Knowledge and Society, 6*, 1–40.

Luft, J. A., & Roehrig, G. H. (2007). Capturing science teachers' epistemological beliefs: The development of the teacher beliefs interview. *Journal of Research in Science Teaching, 40*, 77–97.

Lynch, M., & Woolgar, S. (1990). *Representation in scientific practice*. Cambridge, MA: MIT Press.

Nave, E. (2009). Dialogic teaching and learning: Targets and obstructive factors in dialogic leaning. *The ministry of education web-site. The center for research and information* (in Hebrew) http://cms.education.gov.il/EducationCMS/Units/TelAviv/MarkazMachkarVmayda/lemidadialog.htm.

Ochs, E., Jacoby, S., & Gonzales, P. (1994). Interpretative journeys: How physicists talk and travel through graphic space. *Configurations, 2*(1), 151–172.

Olafson, L., & Schraw, G. (2006). Teachers' beliefs and practices within and across domains. *International Journal of Educational Research, 45*, 71–84.

Peled, N., & Bloom-Kolke, S. (1997). Dialogism in classroom discourse. *Linguistic Plot, 24*, 6–28 (in Hebrew).

Shor, I., & Freire, P. (1987). What is the "dialogical method" of teaching? *Journal of Education, 169*(3), 11–31.

Tufte, E. R. (2001). *The visual display of quantitative information* (2nd ed.). Cheshire: Graphics Press.

Yechiely, T., & Nussbaum, Y. (1998). *Misconceptions and conceptual change in science education* (2nd ed.). Tel-Aviv: Mofet (in Hebrew).

Yoed, Z., & Levin, T. (2007). Epistemological perceptions of children: What do elementary school's children think about knowledge and knowing? *Theory and Practice in Curriculum Studies, 19*, 49–129 (in Hebrew).

Chapter 13
The Laboratory for Making Things: Developing Multiple Representations of Knowledge

Jeanne Bamberger

Reflections are made by the reflecting surface.
Even mirrors are only rarely passive;
They transform images—enlarging, diminishing, dimming,
reversing, bending, twisting—
In implausible, unpredictable ways…
Until you learn to follow the (sometimes circuitous) but always
Orderly course the reflector takes
In reflecting back the sending beam.

JB

Abstract Writing in the context of a book on reflective practice and visualizations encourages reflection on reflection, itself. And this, in turn suggests a paradox: In actual practice, "reflecting" is at best an on-the-spot action, a knowing response to an immediate situation; but more often than not, the knowing along with the moment of reflecting disappear, transparent to and absorbed into their effective result. How then do we learn to recognize, even to see "reflective practice?" And if we do, how do we learn to reflect on these moments that have disappeared without introducing the distortions of hind-sight and "historical revisionism?" These questions or versions of them, will form a continuing and puzzling theme through all that follows.

Keywords Reflective practice • Teachers' learning • Learning as reflective conversations • Multiple representations of knowledge • Laboratory for making things

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13.1 Background

The context for our work with teachers was the design of a project and a place called the Laboratory for Making Things. The place was a large, still empty room in the Graham and Parks Alternative Public School in Cambridge, Mass. The project, as initially imagined, was intended to address a poorly understood but well-recognized phenomenon: Children who are most successful, even virtuosos, at building and fixing complicated things in the everyday world around them are often children who are having the most difficulties learning in school. With the emphasis in schooling on symbolically represented knowledge, it is not surprising that attention focuses on what these children cannot do, and it is also not surprising that the school world sees them not as virtuosos but as “failing to perform.” Starting from a different assumption, I asked: If we could better understand the kind of knowledge children bring to what they do so well, could we help them use this knowledge not as a deterrent but rather as a source for achieving success in the classroom?

We began the project with the teachers. Twelve teachers signed up, with a core group of eight becoming regular participants. The project, as it came into being, was importantly guided by conversations among this group of teachers in the school. I replay some of these conversations as examples of teachers reflecting on their own practice.

We had expected the initial planning period to last perhaps 2 months, but the teachers only felt ready to bring children to the Lab after we had worked together for close to 6 months. Those 6 months turned out to be critical to the teachers learning as well as shaping the form that the Lab, itself, took.

13.2 Moving In

What would the school’s teachers make of ideas born and bred in the academic ivory tower? I had to assume that these adults (who happen to be teachers) were, like the children, used to keeping neatly separate the symbolic knowledge they were teaching and the practical knowledge that they used to make sense of and to navigate the everyday world outside of school. But that being so, to tell the teachers just that, or even to give them curriculum units or lesson plans wasn’t going to help. They were going to have to confront head-on these inner and outer representations that were often at odds with one another. And I was going to have to do that right along with them.

Eight teachers had joined the group in response to a short, quite vague letter we had put in all teacher mailboxes, and a 10 min description at the start of a regular staff meeting earlier in the school year. We offered to pay participants $300 for the year as consultants to the project.

Work began with 2-h weekly meetings in the Lab each Monday after school. The group included the Special Education teacher, and seven regular classroom teachers, who, among them, taught grades K-8 (classes in the school are grouped in pairs—grades 1–2; 3–4; 5–6; 7–8). At the beginning of our work together we talked hardly at all about teaching, about children, or about curriculum projects. Instead, we spent the time making things together and probing our varied understandings of how we did that. We made experiments with electric circuitry, built structures with Lego blocks and tunes with Montessori bells, we struggled to understand how gears worked, and in all of this looked closely at the differences in our respective strategies for both making and describing what we had made. The teachers learned the computer language, Logo, to greater or lesser degrees, using it to make graphic designs as well as melodies and rhythms.

While we had anticipated that after 2 or 3 months the focus of our discussions would turn to planning projects for children, it was only in March of that first year, 6 months after we had begun our work together, that teachers felt "comfortable enough" with their learning to begin work on the design of activities for their students. And it was only in late April or May that all of the participants were finally bringing children to the Lab.

13.3 Going On

I have tried to find a way to tell the reader about the evolution of the teachers' learning without cleaning it up, making it read like a "method" that went neatly forward towards pre-planned goals and objectives. As I had anticipated, I couldn't tell the teacher-participants, either—they had to take time to make of it, individually and collectively, what they could, meanings changing the context in which these ideas lived as their experience changed. Their learning was organic and slow, the germinating process often forgotten in the flow of time.

This sense of lost evolving process became vividly clear towards the end of the second year when we devoted our Monday meeting to a discussion of how we could best introduce new teachers who wanted to join the group, to the work we had been doing. The discussion centered around very practical questions: How can we tell teachers what the project is all about? How can we tell them about our learning through mutual reflection on and appreciations of one another's *confusions*? And how can we help them see how our own learning is reflected in working with students in the Lab? The discussion was revealing in its pervasive sense of elusiveness; and yet for most, this was interestingly coupled with a strong sense of what "the project" was not. One teacher, I will call him David, put it like this:

> We could pass any of this stuff (curriculum projects invented by the group) on to someone else and it would not have the same impetus. But the situation, if we could only describe the situation and the elements of the situation, that's what we need to pass on…Forget the content, it doesn't matter. It's the situation that's powerful.

What was this "situation" and what made it so "powerful?" How had the current group of teachers learned to recognize it, to create it, while still being unable to describe it? What had they learned how to do, how they had changed, what had contributed to these changes, and why was it so difficult to say?

The difficulties the teachers had in making an accounting of their learning (and I shared this with them) was partly in looking for an accounting that matches the conventions, the privileged descriptions, of what such an accounting is supposed to be—one that is consistent with the idealized modes of learning that we are taught to teach. The teachers' learning which was later mirrored in the children's learning in the Lab, had been more like learning that occurs in everyday life: How you have learned happens over time and that "how" is lost when what you have learned is embodied only in the present actions of using it and doing it.

For example, let's say you are building a gate for your fence: You feel the surfaces, the shapes of the "stuff" in your hands; and this seeing/feeling of the materials as they change under your hands through time "tells" you how the materials work, what they can do, what you can do with them. Practicing a sequence of actions on materials, improvising, detecting and correcting as you go along, you find a sequence of actions that works. And once found, this interlocked chain of actions, each one triggered by the one before, becomes a familiar path that you can follow again like following a familiar walk through the woods—next-next-next. Just so, as you practice moving about on a musical instrument, the feel of the instrument's geography becomes a familiar terrain and a practiced sequence of actions that plays a particular composition, becomes a familiar "felt path"—your most intimate "knowledge" of how the piece goes (Bamberger 1981, 1986, 1991).

But in building a gate or playing a piece your actions and the "shapings" of the materials don't stop—the past disappears giving way only to the present situation. So this going-on makes it difficult to take apart actions, to isolate events and to look at the separate features of objects that, in doing it, happen all-at-once; and this going-on also makes it difficult to compare actions, events and objects that happened at different times or in different spaces. How then, do we ever come to "know" or to make static visualizations "out there," to account for what we have learned to do?

If we are to make an accounting of such learning, and, indeed, if we are to help it along, we need to develop strategies for capturing these happenings on-the-wing—albeit risking the potential for distortion that comes from stopping what is always going on. Consider a brief moment in the life of the teacher group—a moment that illustrates the learning that has gone on there.

13.3.1 Reflecting On Practice

During a Monday session one of the teachers, Mary, told a puzzling story about 8-year old Jeff, who, in the process of making a mobile, was trying to balance two different objects on a stick suspended from its middle. As she watched, Mary noticed that he immediately "knew" which way to push the object that was tipping the stick and destroying the balance. Fascinated, she asked Jeff how he did that? Not surprisingly, he answered that he "just knew;" and asking again, he said, "I had a feeling of it, like on a teeter totter." In telling the story to the teacher group, Mary asked: What is it that Jeff "knows" in being able to do that, how did he learn it, and what did he mean by his comment about the teeter totter?

Intrigued, the teachers also became involved in working on the problem of balancing. Like Jeff, they found they could "intuitively" push objects in the right direction to make them balance. But that led them to ask of themselves, what they knew how to do when they did so? As they stepped off the moving path of their own actions to look **at** them, they found themselves facing confusion. Unlike Jeff, they had, of course, learned the formula about "weight times distance," but what they had been taught and learned to say seemed disconnected from what they could directly see and feel. As Mary put it in trying to make sense of what she could see:

> The trouble is, I don't know where to look. What is "the balance"—the stick, the string, the weights, the distance, or the whole thing? And anyhow what does weight have to do with distance; they seem like totally different kinds of things. This is making me very uncomfortable.

This brief moment illustrates my hunch that these adults, like most, were used to keeping neatly separate their school knowledge and their everyday knowledge. But it also holds in it the teachers growing abilities to recognize and to dare to confront the incongruences between these ways of knowing—on one hand, the know-how, the "hand knowledge," that worked "by the feel of it," and on the other, the meanings implicit in learned formalisms such as "weight times distance." Moreover, the group had learned how to ask questions that probed these incongruences even when that made them "very uncomfortable." And most of all they had learned that to get from feelings and actions to the meanings implicit in a formalism, they first had to come to grips with a situation in which they didn't "know where to look." For it is only when you have recognized that as "the trouble", that you can begin to look for and find those objects, features, relations that till then have been hidden from view, transparent to the outcomes of your own actions that you know how to do already.

But how have they learned to do that? I have tried to trace that process by looking back over transcripts of some of the other teacher sessions. What I have found is that through the teachers' work together and the reflective conversations around this work, knowledge gained in their hands-on experiments, along with questions and unresolved confusions raised along the way, became shared experiences, the makings of a common culture. And within this common culture, these collective experiences functioned as the base to which they often returned.

As they moved from one project to another, questions, confusions, and insights gained along the way were used and re-used in new situations. And through this process, more general ideas evolved that always returned again to the particulars of a specific experience now seen differently. These "reflecting transformations"—the images expressed and the visualizations drawn as one person's view bounced off the meanings held by another—were more like the transforming reflections of shapes in moving water.

I have dubbed this going-on of ideas evolving through time, "conceptual chaining." This way of learning became elusive because how you have learned over time is embodied by (exists only in) what you know how to do in the present. This is what made it so difficult for the teachers to describe; it is also, I believe, the quality that David could only point to as "the situation."

What has been my role in this learning process? At the time the discussions in the teacher group were occurring, it was always my sense that I was simply a participant in exploring ideas, asking questions that interested me about the structures we were making and to which, along with the others, we were together quite genuinely seeking possible answers. It was only as I re-read transcripts of our sessions (many of which we taped) and through them re-lived our discussions, that I realized with some surprise that I had been doing much more: I was, in fact, stopping the going-on; and I was doing so by catching on-the-wing those moments in the midst of a conversation or a confusion that held the potential for acting out underlying ideas that I couldn't or didn't quite know how to say. And once I saw such moments, the rumble of my underlying ideas helped me to generate questions, suggestions, probes, prods, and selective confirmations: a question that pulled out the potential for insight in seeing one working system as another, prodded a moment in which the same structure might be seen in different ways, or the emergence of a new visual description that might lead us to take a new view of the situation. In this way I was guiding the course of our mutual reflections, our conceptual chaining, and also the kind of learning that occurred along the way.

And in doing so, I was also playing out with the teachers what they were later able to do with kids in the Lab-learning that has clearly spilled over into their classrooms as well. To give the reader a feel for this process of learning as it unfolded in real time, I record here, excerpts from a conversation that occurred in an afternoon during one of the teacher sessions.

13.3.2 The Situation: Learning as Reflecting Conversations

The conversation occurred early in the project during the course of a regular Monday afternoon session of the Teacher Group. In addition to Susan Jo Russell (my co-organizer) and myself, five teachers participate in the conversation. I have called them, Ida, Lucy, Nina, Sam, and Mary. In tracing the ideas that emerge and the learning they hold, the reader will notice that at any one moment there are several interleaved strands of conversation going on. And as strands gradually make their way to the surface, each develops its own trajectory. Indeed, the dynamic of the discussion and the insights that evolve are often the result of what might be seen as "conversational drift" (and is by some participants). But it is exactly this "drift" that generates that aspect of the group's learning that I have called "conceptual chaining"—the process by which one participant's comments reflect off and are reflected by another's.

In following the conversation, the reader will also observe that, with the help of my interventions, the group's learning plays out many of the ideas that initially motivated the project. For example:

- Seeing resemblances among working systems without being able to say with respect to what; and in making the resemblance criterion explicit, liberating a principle that the working systems share (See Kuhn 1977).

- A computer program functioning as a "transitional object," putting assumptions into question and also revealing previously hidden aspects of hands-on construction.
- Multiple views and multiple modes and media of description that trigger both insight and confusion.
- My role in the conversation: catching moments on-the-wing, I question, provoke, and prod, helping to guide the conceptual chaining as it unfolds.

13.4 Setting the Scene

Before the present discussion begins and earlier in the same session, the teachers had been making experiments with simple circuitry. Working in pairs, they had first built a simple closed circuit that included a battery, wires and a light bulb. Each group then invented their own experiments. For instance, some wanted to see what happened if they changed the size or number of batteries, others experimented with substituting a buzzer or a bell for the light bulb, and so forth. These experiments formed the shared background for the conversation that followed.

The conversation began at what was intended to be a short "break" in the session on circuitry. During this "break", while the group chatted and relaxed with some refreshments, one of the teachers, Sam, showed the others a Logo computer procedure he had made while working at home on his computer. After the participants had admiringly watched the results of Sam's procedure evolving as graphics on the screen, they asked Sam to explain to them how he had made his procedures. Sam obliges with a rather full description of what he had done. But instead of returning to the experiments with circuitry as we had intended, Sam's procedure and the puzzles it generated, turn out to be a jumping off place for a rather intense and wide-ranging conversation that went on for about an hour. I shall include, here, excerpts from only the first part of this conversation, punctuating it with running commentary at critical moments.

13.4.1 A Reflecting Conversation

Sam begins, in response to the teachers' questions, with a description of his computer procedures.

Sam: First I wrote a procedure for "CIRCLE" and I put it in the editor (Sam shows his procedure and runs it) (Fig. 13.1):

```
TO CIRCLE
REPEAT 36 [FD 5 RT 10]
END
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Sam: Then I asked it [the computer] to repeat CIRCLE 40 times, and I added on, RT 10. I asked it to repeat CIRCLE and RT 10, 40 times. I called that procedure CIRCLES. (Sam shows his CIRCLES procedure) (Fig. 13.2):

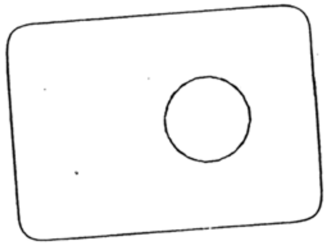

Fig. 13.1 Sam's circle procedure

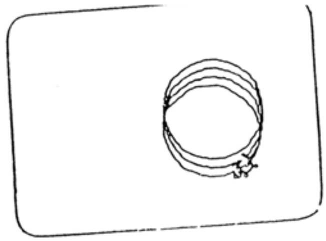

Fig. 13.2 Sam's circles procedure

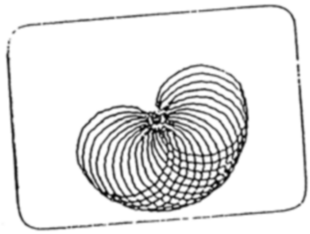

Fig. 13.3 Sam starts up his circles procedure

```
TO CIRCLES
REPEAT 40 [CIRCLE RT 10]
END
```

Sam: So every time it made a circle, the turtle would just angle to the right 10° and make another circle. (Sam starts his CIRCLES procedure, then stops it to show the group what he means by "angled to the right 10°") (Fig. 13.3)[1]:

Sam: So here is my whole CIRCLES procedure. (Sam runs his CIRCLES procedure.) (Fig. 13.4)

Jeanne: Now why did you ask it to go around 40 times instead of 36?

Sam: Well, I just estimated. The first time I did it, it was for 16 times. I think I found that it made it around about halfway, so I asked it to go 32 times and then it didn't go quite all the way…

[1]The command, FD, tells the turtle (a drawing cursor) to move FORWARD some amount (here, 5). The command, RT, tells the turtle to make a Right Turn (i.e., to rotate) some amount (here, 10°).

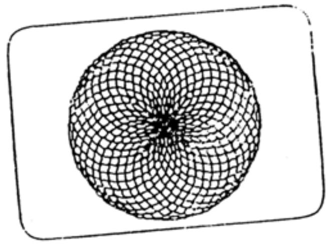

Fig. 13.4 Sam's circles procedure repeated 40 times

Mary: So, yes, it was two circles. One is the individual unit [the circle], and then you repeat that unit 40 times to make another circle—40 circles within a large circle.
Jeanne: And the question is, when will it get back to the original circle?
Lucy: We found [in working with circles] that with a RT of 10, it comes back again after 36 repetitions. But if he got 40 why did it come out perfect?
Mary: I think it's an overlap.
# # #

Already in these first few moments of the conversation, we see multiple views and multiple descriptions developing. As comments are "handed-off" among the participants, each participant is both reflecting and transforming the comments of another. I step in first. My attention is attracted to Sam's use of "40"—the number of times he "asked" the computer to repeat his CIRCLE and RT 10 procedure. My question is interrogating the meaning he is giving to "40" and implicitly his understanding of how his own procedures work. Sam's answer tells us more about his procedure—i.e. how he arrived at the end result: more like making hands-on constructions, he "estimated" in response to the results he saw on the screen.

Mary, working on her own sense of what Sam has told us, reflects back what she sees. And in doing so, Sam's procedural description transforms into objects moving in nested actions—circles circling: "…40 circles within a large circle." Mary's re-describing is a first small instance of a "reflecting transformation" that will lead to others.

Lucy's focus, meanwhile, stays put on my questions which she addresses by looking back at her own experience in making circle procedures with Logo. And from this view, Lucy sees a mismatch between what she "found" earlier and what Sam tells her he has done. In the light of the comparison, she raises a new question: "…why did [40] come out perfect?" Mary, focusing now on Lucy's question, answers it but again puts her answer in terms of objects and actions rather than numbers: "I think it's an overlap."

Both participants are, of course, quite right; what is striking is the differences in their respective views. Lucy, thinking in terms of the numeric values in Sam's procedure, is pointing out that if the turtle turns 10° on each of its repetitions, it will complete the circle ("come back again") after 36 repetitions. Mary's more action and visually oriented view is implicitly saying that with Sam's 40 repetitions, the extra 4 simply go over ("overlap") the first 4. And since we can't see that, the result only seems to "come out perfect."

At this point I make an abrupt shift in direction that begins the next portion of the conversation.

13.5 Two Trajectories

Jeanne: So it's like the earth going around, and then it's like the whole thing going around in the whole year. It's going around itself and then…
Ida: It's like day and night and the seasons. Revolution and rotation. It's beautiful.
Mary: But I don't think that that's what we were doing in doing, in making our butterfly procedure. Because those were larger and larger circles. Yours sort of were all the same size. Our variable was the size, his variable was position. The size of the circle always changed (Fig. 13.5).

# # #

My abrupt shift in direction is only apparently so; I am actually reflecting off of Mary's re-description—i.e., her objects moving in nested action. Letting my initial questions go, I glimpse through Mary's circles circling, a resemblance between Sam's procedures and "…the earth going around...." But without knowing the resemblance with respect to what! Ida, following the trajectory of my reflection, elaborates on it: "It's like day and night and the seasons." And then, pursuing the new trajectory even further, Ida makes our resemblance criterion explicit: Sam's procedure, re-viewed by Mary as circles circling, which I see as the earth turning, all enact the same complementary principles: "revolution and rotation!"

So, in quick chaining, our mutual reflecting results in re-seeing, seeing one working system as another, seeing a resemblance embodied by but still hidden in the materials, till principles finally precipitate out. And as the principles emerge in the context of our immediate and shared experience, principles and shared experience take on new meaning.

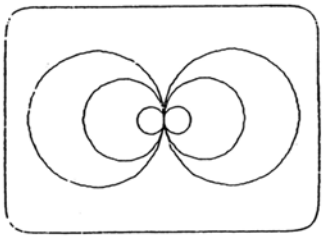

Fig. 13.5 Mary's butterfly procedure

# # #

But meanwhile Mary, seemingly inattentive to this new trajectory and still puzzling over my initial questions, turns back on her own experience in making circle procedures. Like Lucy, Sam's procedure reminds her of a procedure she had made previously—her "Butterfly" procedure.[2] Comparing hers with Sam's the similarities Mary sees between them liberates the features that made their differences: "Our variable was the size; his variable was position." And while accounting for the strikingly different results of the two procedures, Mary, almost in passing, also articulates the formal property they both share: The procedures depend on different uses of the same powerful function—variable!

That is, while both Sam and Mary began with a circle procedure, Sam's use of RT 10 changed the position of his circle on each repetition. In contrast, Mary's use of a changing value for FD (FD :F+2) in her Butterfly procedure changed the size of the circle on each repetition.

So our conceptual chaining moved along by our mutual reflecting leaves a linked trail that diverges into two trajectories. Each of the trajectories, in turn, spawns new views of the material through the emergence of more general ideas. That is, each of these trajectories begins with specific questions grounded in personal experiences with materials—Sam's procedures as well as Lucy's and Mary's. But through reflecting off of one another's personal experiences, seeing similarities and differences among the respective working systems, our conversation winds up and out of the individual experiences to more general principles—first, *revolution and rotation*, then *variable* (Fig. 13.6).

Finally, I noticed my participation in this chaining process. I could have pursued my initial questions in the service of teaching Sam and the others what they didn't know—certain basic geometric principles and how they are played out in Logo geometry. But instead, by letting it go, my initial questions become a jumping off place from which all of us are reflecting back, reflecting on, and building from what we do know. So as the conversation unfolds, I am playing a double role: mutual participant, freely joining in with the others in making my spontaneous associations and

[2] The procedures for BUTTERFLY were these:

```
TO WING1 :F
If :F>4 [STOP]
REPEAT 72 [FD :F RT 5]
WING1 :F+2
END
TO WING2 :F
IF :F>4 [STOP]
REPEAT 72 [FD :F LT 5]
WING2 :F+2
END
T BUTTERFLY
WING1 1
WING2 1
```

NOTE: :F is the "variable." The wing procedures begin by giving :F a value of 1 (e.g., WING1 1), which makes the smallest circle. They then add 2 to that value (:F+2) giving :F a value of 3 to make the next larger circle, and once more add 2, giving :F a value of 5 to make the largest circle.

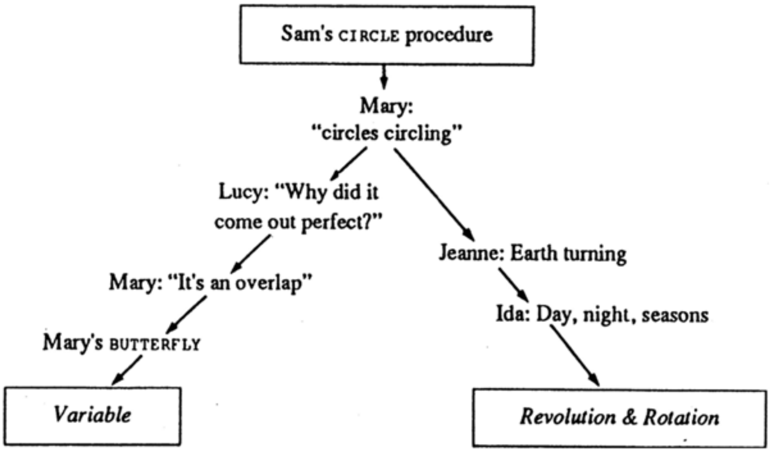

Fig. 13.6 "…trajectories, each of which spawns a new view"

views known; and also watchful listener—looking for moments to grab on-the-wing so as to provoke, probe, prod and reinforce germinating ideas. And, in going on with the conversation, I focus especially on those moments that might encourage the participants to see another familiar working system in a new way.

13.6 Shifting Meanings

Jeanne: Are there any variables, here, in your circuits?
Mary: Are there any variables in....
Jeanne: In what you were just doing before?
Sam: Yeah, there were variables.
Jeanne: Like what?
Sam: Like making one bell ring, making the other bell ring, trying to make both bells ring simultaneously.
Susan Jo: Those are differences—different things that are happening, but I don't....
Sam: Oh, so like using circuits to do different things.
Jeanne: Yes. Each one of these—bell, buzzer, light bulb—you could think of as a variable in the circuit.
Susan Jo: That doesn't necessarily mean the same thing to me. Like in Sam's circle, the variable he uses—the number of repetitions as 16, 32, then 40—is… it's doing the same things but the number of times it does it changes. That's a kind of thing that stays the same, but the amount is varied.
Ida: A variable could be the amount of batteries.
Jeanne: So you vary the amount of power. Well, what if you just substituted the bell for the buzzer? That is, everything is the same except…would that be a variable?

Nina: Well, that's changing more than…if you're using a battery…you're increasing the light, or increasing the battery. Whereas if you switch—you use a bell or a buzzer—you're changing the whole…you're changing more, aren't you?

Ida: Sometimes you use a bell and sometimes a buzzer. But then the variable is what is doing the work…

Susan Jo: So the type of work that's being done varies.

Sam: Yes, it would be. It would be the same thing; you're just working in a different medium.

Jeanne: So the light bulb was one medium and the buzzer another? But the circuit stays the same.

Ida: This is just substituting…substituting something different.

Mary: So we're saying if shape…if visually it's a totally different form, that doesn't feel like a variable anymore. 'Cause that's really…functionally, the bell and the buzzer are pretty similar. It's just…they look like they're different species somehow…

Ida: In the computer we're using variables to change quantities of things. But with the color…shape…those are qualities…attributes…

Jeanne: But if you start with the circuit as the basic thing, then changing bell/buzzer doesn't make very much difference. But if you look just at the bell and the buzzer, they're very different things.

Susan Jo: Well the structure stays the same, but the function…

Jeanne: It depends on what you're looking at.

13.6.1 Comments on Our Conversation

Catching Mary's use of the term "variable" as it passes on-the-wing, I pluck it out and use it as a foil to prod the participants' understanding of the term. I do so by asking them to posit a function for "variable" within the circuitry materials that are still lying about on the table: "Are there any variables, here, in your circuitry?" At the same time I am "visualizing variable" as a foil to help the group experiment with the possibilities for seeing one familiar working system as another. The ploy turns out to be a pivotal one. The participants find themselves following a "thought experiment": What will happen to the meaning they are giving to "variable" as a function embedded in Logo computer procedures if they carry "variable" across and imagine it, visualize it, as potentially a function embedded in the circuitry with which they have just been working?

The experiment immediately exposes the term for scrutiny. At the same time, features and relations come to the surface that were previously hidden, transparent to the goals of all-at-once actions. And in carrying out this experiment, the computer is playing the role of "transitional object." With Logo procedures as one of the two working systems through which we are interrogating the meaning of "variable," the thought experiment helps to bridge the gap between meanings implicit in symbolic expressions and meanings embodied by materials and actions on them. Unlikely as it would have been if we had planned a "unit on variable", variable becomes the focus of the group's animated discussion.

Sam's initial response followed by the quiet confrontation between Susan Jo and me, the leaders of the group, opens up the field and sets the terms for argument, speculation, and side-taking. The arguments hinge on visualizing what each person takes as a kind of thing that can change, along with a kind of thing that stays the same. For Sam, what changes are concrete objects and actions: "Like making one bell ring, making another bell ring...." Susan Jo (who is also our math specialist) disagrees: "Those are differences—different things are happening...." I elaborate on the object-meaning Sam is implicitly giving to variable, suggesting also a concrete object that might be staying the same: "…bell, buzzer, light bulb you could think of as a variable in the circuit."

Moving in, Susan Jo makes her view more clear. Arguing for its formal and canonical meaning as used in Sam's procedures, a variable is not a "variable" object but rather a kind of action (e.g., REPEAT) that stays the same but the amount (16, 32, 40) varies.

As the conversation goes on, it is important to notice that our conversation along with the emerging meaning of this quite abstract notion, variable, is always grounded in specific materials that we can see, that we are all looking at and trying to make sense of. Continually returning back to these materials in our conceptual chaining, seeing now one aspect now another, the materials and their relations serve as the vehicles through which the participants carry themselves beyond what they know already to a new view. Searching for one another's meanings, each participant is at the same time informing his/her own. It is interesting to notice, too, that differences among the participants are made more friendly, less confrontational by attributing them to "feelings" rather than reasoned thought or conviction: Mary: "…that feels like a variable;" Ida: "…those things don't feel like variables…it would feel like a variable if…"

And as the conversation moves back and forth, each person actively reflecting the other, participant's comments continue to spiral up and back down between concrete examples and generalization. For example, Ida makes a general comment as she puts her finger now on the "difference criterion" underlying our disagreements—quantities vs qualities: "In the computer we're using variables to change *quantities* of things. But with the color…shape…those are *qualities*, attributes." Her more general comment depends on, reflects on the specific examples that others have used in making their arguments. For instance, some people talk about the amount of batteries or of power, and the number of circuits or power sources; while others refer to qualities they can see like color, shape, medium: "…if visually it's a totally different form, that doesn't feel like a variable anymore." Indeed, the distinction implicit in our disagreements which Ida makes explicit, quantities vs qualities, points to a general distinction that is often seen as critical in distinguishing between working in the virtual world of the computer and working in the real time/space world of hands-on materials.

Picking up on Ida's distinction, reflectively transforming it, turning it around, I propose another view: "…if you start with the circuit as the basic thing, then changing bell/buzzer doesn't make much difference. But if you look just at the bell and the buzzer, they're very different things." And pushing the level of generalization a little higher, the rumble of my covert ideas (multiple representations, multiple seeings) bubbles to the surface: "It depends on what you're looking at." But notice that "higher" is in no sense "better." For it is exactly the waves up and down (from materials to generalizations and back) and the resulting reciprocity among these moves that gives both the materials and the generalizations credibility and meaning. And through our conceptual chaining, these moves with their shifting meanings, are also carrying the potential for learning.

13.6.2 Two Insights

But what was being learned? Surely, people were learning different things differently. Jumping ahead to the end of the conversation (which continued on for some time) we find that both Mary and Susan Jo have each made discoveries but they are of very different sorts.

Mary's insight seems to come from following the winding path of our conversation and at the same time her comments embody in them the very processes that have given rise to this winding path—reflecting transformations, seeing in multiple ways, moves up and down between materials and generalizations. Mary's comments come in response to a question by Susan Jo who at this point has become restless with our "conversational drift:"

Susan Jo: I have a question. What's in this about seeing variables in different places, that we can use, or would we use in teaching? Is this a notion that would be valuable to kids?

Mary: It's critical in understanding where a kid is at. Because you're teaching this, and the kid is giving these cockamamie answers. And then if you can, like go over there, I mean over where the kid is looking from, and you look out from there, that's exactly what he ought to be seeing. And then what the kid was saying makes perfect sense. So I don't think you can teach the kid about the variable, but you can try to find a path into what the kid is seeing… And we can't just react....

The links in our conceptual chaining have helped Mary to see and to help other's see what I could not have told them. And this is so because while Mary's insight follows the emerging path of our conversation, she has reflectively transformed the materials and ideas that carried it along: her insight is importantly grounded in the "materials" she knows best—events that happen with children in the real world of school. And with this grounding, those vague, inaccessible rumbling ideas like the importance of paying attention to different ways of seeing, describing, and making sense of the world, become her own—practical, relevant, everyday events that the teachers, along with Mary, can recognize and feel.

For Susan Jo, in contrast to Mary, the conversation has all along been about the meaning of the term, variable. Her insight, that seems to have been slowly germinating (the path of the conversation serving as nutritive medium), carries the conversation back to the initial controversies generated by Sam's computer procedure. Susan Jo's own previous work as a teacher, now reflected in the multiple mirrors of the group's discussion, helps her see in a new way, what she knew already:

Susan Jo: I'm still trying to figure out whether I think substituting the bulb for the bell is a variable. But it just struck me that when I did this sort of stuff with my kids—you know, varying the battery and the bulb gets brighter—but the *constantness* of the circuit itself is something that…that the thing you stick in there doesn't matter, never struck me before because we never had anything but bulbs so it wasn't in fact a variable. And yet it's so important…the constantness of that circuit is such a fundamental thing. But if you don't vary the function of the things it's operating with, you never get to that.

And I, responding to Susan Jo, use her comment to wrap up the conversation by turning it back on itself:

Jeanne: Yeah. It's like what just happened here. I mean we started talking about the.. the…the thing that Sam had done, and that made us start thinking about this stuff [circuitry]. But if we hadn't had both things—Sam's computer procedure and the circuitry stuff—we might not have gotten to the issue of…the business of a constant and a variable might not have leaped out if we had just been sticking with one thing, this circuitry.

13.6.3 Following the Path into the Lab

But I began the project and this chapter with ideas and hopes for children's learning. What, then, can be said about that? I have suggested several times that the teachers' work in our sessions has been mirrored in their work with children in the Lab. I see this most clearly in Mary's work with the children. Mary, who is in fact Mary Briggs, is one of the Special Education teachers in the school, working with students who have been identified as having "learning disabilities." Over the past 3 years, Mary and I have together worked with five or six children with whom she works on a daily basis and whom she brings to the Lab after school for 2 h on 1 day each week to work together with me. My conversations with her, together with actually working in the Lab with children has been a major factor in helping me to see how ideas born in the ivory tower can be put to work in the real life of school. I will conclude this chapter with a few remarks and a short example of Mary's learning as it was reflected in her work with one child whom I will call Ruth.

Ruth joined our group when she was 8 and having real troubles in her regular classroom work. She had severe difficulties learning to read, she often disturbed her teacher by responding to directions or explanations with, "I don't understand, really," and as we saw in the Lab as well, she had serious problems putting into words what she was thinking about. Typically, in trying to say what she was thinking, Ruth would start up, then stop, then say, “I forgot,” or “I don’t know,” or “Oh, forget about it.”

In the Lab it gradually emerged that these moments of inarticulateness were in fact critical moments in which Ruth was germinating an idea. As such, they became for Mary and eventually for the other children as well, a signal to stop what we were doing so as to help Ruth find out what it was she was thinking about. Smiling and often with a knowing laugh, Mary would say, “I’m sure you haven’t really forgotten. Take your time, dear, it’s worth it.” And with this encouragement, along with the other children’s respectful patience, Ruth’s ideas would haltingly emerge, often in a form that was difficult to understand at first. As time went on, it became clear that the issue was not just Ruth’s difficulties with words, although that was also true. As it turned out, Ruth’s ideas were very complex, and often at an extraordinary level of abstraction: It seems that she, unlike many of the rest of us, could, in her imagination, stop the “going-on” of her actions and the actions of the materials themselves—those that she could directly see and feel—in order to “mentally feel” and to coordinate relations among relations. It was these multiply interacting relations that would account for the specific workings of structures we were making and trying to make sense of—rhythms, gears, pendulums.

But to find words to express this feel for what she could only see in her mind’s eye was understandably difficult (that’s why the formalisms of science have their privileged status). And that Ruth’s understanding was in a very real sense a “feel for,” and not visible in the movements of the objects themselves, came through clearly in the expressive gestures that often accompanied her halting words (See Piaget 1962).

Through Mary’s encouraging probes, it also became clear that Ruth’s behavior in the classroom was deceptive, indeed: Her expressed inability to understand the teacher’s explanations stemmed not from an intellectual deficiency but from her own intellectual demands—she needed to know more and probably differently. Or as Mary often put it later, “Ruth needs to know the whole, the why, before she can begin to deal with the details, the parts.”

How did Mary come to understand these qualities of Ruth’s thinking? She did so, in part, by mirroring in her own reflecting way, the kind of learning we were practicing in the Teacher Group, and by following the paths that had led to her generative insights, which interestingly, Mary also had her troubles articulating. Recall, for instance, her insightful but groping comments in response to Susan Jo during our earlier conversation about the value of discussing variables with kids: “…if you can, like go over there, I mean over where the kid is looking from, and you look out from there, that’s exactly what he ought to be seeing. And then what the kid was saying makes perfect sense. So I don’t think you can teach the kid about the variable, but you can try to find a path into what the kid is seeing… And we can’t just react....” I illustrate with one short instance:

During the second year of Ruth’s work in the Lab, we were working with two huge meshing gears that children in another group had made out of cardboard. There was one smaller gear (8 teeth) and one larger gear (32 teeth). As Ruth and others were playing with the gears—turning them around, watching what was happening—the following conversation ensued:

Fig. 13.7 Ruth shows "… how each tooth goes in like that"

Mary:	Now which of these gears do you think is going the fastest?
Several children:	The smaller one.
Ruth:	No. Both of them are going at the same speed.
Sid:	But the smaller one is going fastest.
Mary (to Sid):	You say it's going faster, huh?
Jeanne (to Ruth):	You said same speed?
Ruth:	Because look, you can't make this one (the smaller gear) go faster. Every time this is going…Oh, you mean how fast it's going <u>around</u>?
Mary:	Well, I don't know, what do you think?
Ruth:	What kind of fastest do you mean?
Mary:	What are the choices?
Ruth:	Well there's one kind of fastest where you can say for each tooth…
Mary:	Wait, one kind you can say…
Ruth:	Like for one kind of fastest you could say—like you could go—you could say how—like how each teeth goes in like that, ya know what I mean? (Fig. 13.7) And one kind of fastest, you could say how long it takes for this one (the smaller one) to go around.
Mary:	Hmmm. So if you say it's the kind of fastness with the teeth, then which one wins, which is the fastest?

Sid: The smaller one.
Ruth: No, they both are going the same speed.
Mary: O.K. And what about if you say which goes around the fastest?
Ruth: The smallest one.

It's important to note, here, that Mary was, herself, not quite clear about the workings of the gears and, indeed, had at first been hesitant about the whole project. So, in asking her questions, Mary was not testing Ruth to see if she had the right answer, Mary was genuinely interested in hearing what Ruth had to say; maybe, in the process even helping herself to clarify and inform her own understanding. This attitude, this way of listening to Ruth, was Mary's way of "finding a path into what the kid is seeing;" and in following that path she was also helping Ruth to find words to say what she felt.

And what she "mentally feels" turns out, as was often the case with Ruth, to be of a complexity that helps to account for the difficulties she has in putting her ideas into words. What Ruth has understood, albeit still to some extent embodied in the materials and expressed in a way that sounds quite different from canonical "privileged descriptions," is the principle of linear velocity ("…how each teeth goes in like that") functioning simultaneously with angular velocity ("…how long it takes for this one to go around"). And in order to account for the two kinds of "fastness," she needed to get off the path of the gears' actions and her own, so as to differentiate and then mentally coordinate actions that she could not, at any one moment, directly see and feel.

13.7 Looking Back

Looking back to my initial ideas, those that motivated the project in the first place, I realize that Ruth's learning difficulties also involved a mis-match between inner mental visualization and outer descriptions of it, but in ways that I could not have imagined before. My focus earlier had been on the problems that children or adults with well-functioning "sensory-smarts" might have in making sense of the formal, symbolic languages spoken in schools. But Ruth's troubles suggest a different kind of mis-match. Hers was a mis-match between, on one hand, the relations of relations that she could somehow find and feel in the materials but which could only be represented in her mind's eye, and on the other, the words she had available to say what she could mentally see.

The two kinds of problems converge in illuminating the special qualities of symbolic expressions—those qualities that probably explain why, through the long history of science, they have come to be: Symbolic expressions allow their users to say, to describe, just those relations of relations that we are able to find only when we are able to step off the singular felt path of our actions, stop their going-on. Reflecting on what we have seen, we can, but only in imagination, hear or see, for example, two simultaneous motions (angular and linear). And rather than leaving them undifferentiated so that they merge into a single stream of motion, we pull them apart, look at each one separately, and then coordinate them in a single higher level structure. And that complex structure, still without collapsing the two streams of motions into one, encompasses them both. And it is these "higher level" structures that can best, perhaps only, be expressed in the formalisms, albeit static in themselves, that have become the privileged languages of science.

It would seem, then, that the differences between the problems of builders in the real world and in real time and the problems I have come to see in watching Mary and Ruth, are these: Real-time hands-on builders have not yet acquired inner mental representations that might make accessible to them the kinds of structures to which formalisms refer; others, like Ruth, can glimpse the kind of structures to which formalisms refer, but they have not yet learned to see in these formal expressions, what they have already glimpsed in the phenomena, itself.

And to continue this conceptual chaining, it was Ruth's explanation, that still stayed close to the materials, nurtured by Mary's patient questioning, that later did indeed help Mary to understand the principles underlying what Ruth had discovered. And without saying more about it, I suspect, too, that seeing resemblances between one working system and another (Sam's procedure, the earth turning) and then making the resemblance criteria explicit so as to precipitate out a more abstract principle that they both share, is in some important way practicing the very same kind of intellectual activity that is involved in abstracting out two motions from the single perceived motion of gears, rhythms, or pendulums. And finally constructing a further complex structure that is neither of them but accounts for them both.

Ruth will be in sixth grade next year. She is reading well, and while still shy and sometimes a little "dreamy," there is no longer any doubt about her abilities. I end this accounting with what I will call Ruth's "testimonial." At the last meeting of Ruth's third year in the Lab, Mary asked each of the children to say "one thing" they had learned during their time in the Lab. Ruth was eager to speak and what she says creates another link in the chain of reflecting transformations. It is particularly interesting that for Ruth, who still has difficulties saying what she is thinking, the time she spent "talking about something" is a very important part of what she has learned, how she did that, and even why it was worth doing. Reflecting back and reflecting on her experience in the Lab, Ruth's response to Mary's question tells us perhaps better than any of us could, what "the project" is all about and what "reflecting" is all about, too.

Ruth: You have to do a lot of thinking. I like it that everyone does it kinda on their own. And it's so funny to compare ways cause you think you've got the right answer, but you don't have, you've just got one answer. And talking about something. When you talk about it, you learn more from yourself. Like you know why, but you can't explain it. Cause when you talk about something, you have to think about what you're thinking about or what you have in your mind. And you know you have a right answer or whatever, but when you say it.... When you say it out loud you kind of think of it yourself in different ways—of what you did even when you were in first grade. Even the next time I go do that (points to pendulums), I might think about it in a different way. And explaining it, you feel good.... you get what I mean?

Mary: Ruth, I get you so well!

References

Bamberger, J. (1981). Revisiting children's descriptions of simple rhythms. In S. Strauss (Ed.), *U-shaped behavioral growth*. New York: Academic.

Bamberger, J. (1986). Cognitive issues in the development of musically gifted children. In R. J. Sternberg & J. E. Davis (Eds.), *Conceptions of giftedness*. Cambridge: Cambridge University Press.

Bamberger, J. (1991). *The mind behind the musical ear*. Cambridge: Harvard University Press.

Kuhn, T. (1977). *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Piaget, J. (1962). *Play, dreams, and imitation*. New York: Norton.

Part V
Overview

Chapter 14
Developing Science Teachers' Representational Competence and Its Impact on Their Teaching

John K. Gilbert and Billie Eilam

Abstract This book has consisted of a series of chapters that describe and discuss the knowledge that has been accumulated regarding teachers' meta-representational competence (MRC) and the pedagogies within which it is displayed. Relatively little literature on this theme has so far been published. This book ha identified the gaps in knowledge that must be filled, for example: the nature of the curriculum through which MRC can be taught; how MRC enables a teacher to respond to students' difficulties in understanding and producing representations. In this, the last chapter, key themes in the use of representations in teaching and learning are revisited and integrated into a whole.

Keywords Meta-representational competence • Internal and external representations • Representational modes • Approaches to teachers' education for MRC • Science teachers

14.1 The Increasing Importance of Visualisation

These challenges are both important and pressing. Ever since explicit science education began, initially in Western Europe and perhaps in the sixteenth century, it has been dominated by words, both spoken by a teacher and written in a textbook, with some tactile learning taking place through practical work in laboratories and

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elsewhere. The inclusion of illustrations of all kinds – pictures, diagrams, graphs – in verbal presentations and textbooks has gradually expanded as printing has become cheaper, more versatile, and lately, much more colourful. However, it is the advent of the personal computer, with its ever-expanding memory capacity, that is having the greatest impact. There is now little restriction on the number and complexity of the visual representations that may be included in close proximity to words in written text or oral presentation. Educational systems, responding with their usual glacial slowness (Van den Akker 1998), are gradually including the use of computers, and, by implication, visual representations, in the teaching methods used in well-funded schools. The full impact of information technology on formal education has yet to be felt. However, on the positive side, the informal education of both school-age students and adults is already making extensive use of computers, and hence of visual representations, in the self-directed learning activities that are increasingly available.

14.2 Visualisation as Internal and External Representation

Given their importance in learning and teaching, we must clarify the meaning of the words 'representation' and 'visualisation'. Whilst the Concise Oxford Dictionary provides one definition for 'representation' i.e.

> 'A statement made to convey meaning' (Pearsall 1999) (p. 952)

this does not specify what a 'statement' is. Moreover, two distinct definitions are provided of 'to visualise' i.e.

> '1. Form a mental image of, to imagine. 2. Make visible to the eye' (Pearsall 1999) (p. 1301)

The first of these definitions refers to a visualisation as being a representation of an object in the brain, in either the presence or the absence of that object, and may also be called a 'mental image' or, more generally, an 'internal representation'. The second meaning refers to that that representation which is perceived by the eye, an 'external representation'. There is considerable evidence that understanding an 'external representation' and a corresponding 'internal representation' share the same mental processes. In what follows, we will use the word 'visualisation' to refer to either an 'external representation' or an 'internal representation', dependent on the context in which the word is used.

14.3 The Modes of External Representation

Although the physiological nature of internal representations is still the subject of inquiry and intense speculation by neuropsychologists, a rough taxonomy of external representations can be produced in terms of the media in which they are produced. The five generic modes, each of which has a distinct capability to produce an external representation (each having a distinct 'code of representation') are:

14.3.1 The Verbal Mode

The verbal mode plays a major role in all external representations in science, for two reasons. First, speech is the most widely used mode of representation for all human communication. As such, it usually accompanies the use of a representation in any one of the other modes. Mammino (this volume, Chap. 9) emphasises this vital synergy between language and other forms of representation. She points out that a lack of language mastery makes it difficult for students both to understand the textbooks with which they are provided and to express ideas in their own words. Second, a major component of the verbal mode is the use of analogy, this playing a major role in science and science education generally, and most importantly, when abstract ideas are being presented. However, if students are not familiar with the source from which the analogy is drawn, or if an inappropriate analogy is used by the textbook or teacher, then misunderstanding may result, indeed, misconceptions may be acquired. Liu, Won and Treagust (this volume, Chap. 5) provide examples of where these errors lead to confusion, rather than clarity, in students' understanding of diagrams in biology.

14.3.2 The Concrete/Material Mode

This mode is most commonly used to present a tactile, three dimensional representation of a physical structure, the emphasis being placed on its detail and three-dimensional nature e.g. a ball-and-stick representation of a crystal, a 'cut away' representation of the veins/arteries relationship in the blood circulation in body, a 'blown-up' representation of a micro-electronic circuit.

The universal availability of computers with large memory stores has enabled the development of software packages to be developed of virtual versions of concrete/material representations. The three-dimensional nature of the representations is indicated by the inclusion of visual clues (e.g. relative distance, shading) from which that nature can be inferred once the appropriate code of representation is known. These virtual representations can be inverted, rotated, and orchestrated into dynamic systems, to show spatial and temporal change. This is done, for example, in the 'slowmation' system produced by Loughran (this volume, Chap. 4). Such virtual representational systems are playing an ever-greater role in science education, although doubt must remain over whether the understanding that can be acquired from them is of the same quality as tactile learning.

14.3.3 The Visual Mode

The scope of the visual model includes a wide range of different forms, many of which are not readily distinguishable from each other. They are most commonly referred to collectively as 'diagrams'. The taxonomy of diagrams has been produced by (Hegarty and Carpenter et al. 1991), who divide visual representations into three broad classes based solely on their appearance: 'Iconic diagrams',

where

> 'the spatial relations of the referent object are isomorphic to the spatial relations in the graphic depiction'.

Examples are photographs and line drawings: the visual representation looks like that which is being represented i.e. the referent.

'Schematic diagrams',

which

> '… depict very abstract concepts and rely on conventions to indicate both the components and their organisation …'

Examples are Venn diagrams, flow charts, linguistic trees. The conventions of representation bear no physical resemblance to what they depict, such that they must be fully known if the system is to be used;

'Charts and graphs',

where

> '… the referent to be depicted is some set of isolated facts or records that are typically quantitative'.

Examples are line graphs, polar charts, pie graphs. Entities are presented abstractly, the emphasis being on their number rather than their nature.

This approach to classification has three drawbacks. First, it is only concerned with first-order distinctions between types of representation based on their ontological composition, whereas many diagrams are hybrids of two of them e.g. weather forecasts are often iconic diagrams that include schematic elements. Second, it is assumed that they will be interpreted in isolation, whereas, in common practice, the diagram and accompanying text or speech complement each, to some extent at least. Third, it also assumes that the entities depicted in diagrams will only be stationary, whereas many of them move in space or time. This scheme was proposed before the advent of personal computers made dynamic simulations of events commonplace.

14.3.4 The Gestural Mode

In the gestural mode, the body, or some part of it, is used, consciously or unconsciously, to depict some aspect of a representation. Although non-verbal communication is very important in the analysis of interpersonal relations, the gestural mode of representation is under- valued in education and hence is under-researched. This under-valuation probably arises from the fact that gestures are normally accompanied by speech and are perceived to be subordinate to that speech. Nevertheless, gestures do seem capable of reinforcing the meanings intended by speech. For the hard-of-hearing, gestures are invaluable. Whilst they can be made with any part of the body e.g. shrugging the shoulders, averting ones gaze, the variety of gestures most commonly used in science education are produced by the movement of hands and arms.

14.3.5 The Symbolic Mode

There are two specific 'symbolic modes': the mathematical and the chemical. The use of the mathematical mode of representation, most commonly referred to as the 'mathematical equation', is most highly prized in science and science education, for it can be used to:

- build succinct quantitative representations of a topic of interest in terms of the incidence of the variables that describe it's behaviour. For example, the Ideal Gas Equation ($PV = nRT$). Thus, a measure of pressure (P), when multiplied by a corresponding measure of volume (V) is the same as the corresponding measure of its temperature multiplied by a constant;
- provide a language with which to argue about the relationships between those variables. The equation provides a factual base against which the reasons for the relationships can be explored;
- undergo a process of manipulation, of development, so that it can be used to explore the possible behaviour of a phenomenon and hence to make predictions that are capable of being empirical tested. The equation can be rearranged so that the values of P, V, T, for a fixed amount of a gas can be anticipated and the deviance from ideal behaviour quantified.

The intellectual power of the mathematical mode is such that a person cannot become a highly productive scientist without having great skill in the use of its variants.

Chemical equations are the other form of symbolic representations. This indicates the quantitative relationship between the reactants and products of a chemical reaction that proceeds to completion. After several hundred years in which conventions for writing chemical equations have evolved, that representational convention adopted by the International Union of Pure and Applied Chemistry is now used in all formal communications about chemical reactions (IUPAC 2013).

14.4 The Notion of Meta-representational Capability

As internal and external representations play a major role in all teaching and learning, it is important that teachers and learners of science are competent in all the knowledge and skills that these phrases implies. When discussing what this competence entails (diSessa and Sherin 2000) say that:

> 'We add the prefix 'meta' to denote our more encompassing aims. We are interested in whatever students know *about* representation (*meta*- representation), whether or not it con-

> cerns instructed representations … The prefix meta may invoke a connection to meta-cognition. However, we do not intend our use of meta-representation to make this link. There may be meta-cognitive or reflective components of MRC, but … this is an empirical matter to be investigated, not an assumption' (p.386)

It is therefore necessary to define, by example, the scope of MRC.
A fully meta-representationally capable person should be able to:

- Demonstrate an understanding of the 'codes of representation' for the five major modes of representation. That is what kinds of entities may be depicted and how, what types of relationships (e.g. angle, distance, causality) between them can be shown, what types of relationship cannot be shown;
- Demonstrate a capacity to translate a given model between the five modes of representation in which it can be depicted. For example, to be able to relate a visual representation (a diagram) of the human torso to a concrete/material representation of it;
- Demonstrate the capacity to construct a representation within any of the five modes. For example, to produce a visual representation of the human torso from a concrete/material representation of it;
- Demonstrate the capacity to solve novel problems with the use of suitable representations. For example, to produce a full description of the layout and behaviour of the lungs and heart, making use of visual and concrete/material representations of it (Gilbert 2008)

Such a person could be said to have achieved full meta-representational competence. Having this degree of competence is one of the major indicators of expertise as a scientist. If we know how such competence is developed, then it will be possible to design a scheme of education to achieve it.

There are a number of individual, notionally separate, issues relevant to meta-representational competence that have still to be addressed, as have emerged in earlier chapters. These are the need to explore more fully:

- a broader range of the many issues that govern the nature and development of meta-representational competence;
- the value of individual representations in the understanding of the nature of and the relationship between the macro, sub-micro, and symbolic levels of representation;
- the determinants of the cultural acceptability of the various types, origins, and uses, of representations;
- the interdependence of the development of understanding and use of language and of representations.

It is only when these issues have been substantially addressed that it will be possible to produce a systematic overview of representational competence, as is discussed next.

14.5 Theoretical Underpinnings to the Development of Meta-representational Competence

The development of meta-representational competence is based on three distinct ideas.

14.5.1 The Manipulation of Signs

The idea is concerned with the nature of the entities that are manipulated in both external and internal representations to produce meaning. These are signs, the basic material of the science of semiotics, first defined by (Pierce 1931) and presented in this volume by Loughran in the following terms:

> 'meaning is made when a sign represents an object (such that): i) an object or referent is the concept or content being represented; ii) the sign that is created is called a representation; iii) the meaning generated from the sign is called an interpretant'

Each of the five modes of representation can be thought of as distinctive signs or as an assembly of such signs, for this language convention makes it possible to discuss how signs are associated with meaning. To be fully meta-representationally competent, an individual must know the relation between the objects represented (the referents), the representations produced, and the interpretants (the resulting meanings) for all the modes of representation.

14.5.2 The Acceptance That Understanding Results from the Response to Stimuli, Whether External or Internal

The overall sum of the stimuli that can be experienced by a person may be divided into two types: the verbal, words received either orally or in written form; the non-verbal received from gestures, images (of objects, diagrams, graphs etc), sounds, or by touch (Paivio 1986) has produced a model, Dual Coding Theory, for how these stimulate – or rather the signs that are generated from them – are processed by and stored by the brain. Within the verbal system, the meanings of words are stored separately but 'associative structures' can be formed amongst them, such that complex phenomena can be understood through the existence of such linkages. Within the non-verbal structure, visualizations etc are also stored separately, and associative structures can again be formed amongst them, again such that complex phenomena can be understood. Perhaps most importantly, referential links can be formed between the two systems, so that their different representational capabilities can be brought to bear on one phenomenon. The output of the two systems, whether verbal or non-verbal, is informed by the associated and/or referential structures that have been formed within and between them. The strength of the Paivio model is that it recognises the equal value for understanding resulting from the processing of signs generated in both the verbal and non-verbal systems.

14.5.3 The Exploration of the Pedagogic Implications of the Making Meaning from Signs

The third major underpinning for meta-visual capability concerns the mechanism by which meaning is made from signs and hence the pedagogic approaches that may be adopted to increase the precision, the accuracy, of that meaning. The general precepts of this mechanism are provided by constructivist psychology. The main ‘school’ of constructivism on which attention is currently focused assumes that people learn by active mental engagement, by relating new knowledge to what is already understood. This takes place in a social context. It places less importance on the significance of the individual in that process, as compared with that of the surrounding society. The all-important social dimension to learning is moved centre-stage in the ‘social constructivist’ approach of Vygotsky (1978, 1986). This sees learning as a process of social enculturation of a learner by interaction with an authority e.g. a teacher. Only that knowledge which lies within the ‘zone of proximal development’ of the learner, an unclear phrase that seems to mean ‘the range of possible new knowledge that is sufficiently related to existing knowledge that it can be understood’.

In the social constructivist model, it is assumed that successful learning results from a high level of interaction between the teacher (or other social agency e.g. a book) and the taught, such that the mental activity of the later is prompted and shaped by the former, leading to the gradual build-up of knowledge through the use of signs, with verbal and visual input playing complementary roles. In this volume, Mammino provides extensive and detailed examples of how this process of interaction and knowledge development take place. In short, signs are acquired both verbally and non-verbally, being related to each other through the classroom activities that support the social construction of knowledge. That is, by the posing and answering of verbal questions, the construction of representations of all types, and by the discussion of the cognitive value of these products by students and the ‘social agent’ (the teacher).

14.6 The Significance of Personal Meta-representational Capability for Science Teachers

Given the central importance of visualisation in science education it is vital that science teachers are themselves fully meta-representationally capable. This would entail them being conversant with the operation and implications of the Peircean notion of signs, appreciating the complementary nature of the contributions to meaning made by both the visual and the non-visual modes of experience of stimuli, and by being able to deploy the principles of constructivism in their classrooms. There are three reasons why the acquisition of these capabilities is so important.

14.6.1 The Notion of 'Levels' of Representation

The first reason relates to the 'levels', the types, of representation that are used in science and hence in science education. In chemistry and chemical education, three levels of representation are used (Johnstone 1993). These are the:

- Macro level. This consists of samples of exemplar chemical phenomena (named pure elements, compounds, or mixtures), together with their empirical properties, for example, their mass, density, concentration, pH, temperature .
- Sub-micro level. The empirical properties of the macro level are explained at the sub-micro level by the use of models in which the arrangement of the entities of which they are thought to consist (e.g. atoms, ions, molecules, free radicals) are depicted as external representations. Models of the sub-micro level also include the distribution of bonding electrons resulting in the depiction of inter- or intra- entity shapes.
- Symbolic level. At the symbolic level, the explanatory models at the sub-micro level are simplified to the use of signs (e.g. Mg) to represent a particular atom species, the use of superfixes to indicate electrical charge (e.g. Cl^-), the use of subfix letters to indicate the physical state of entities (e.g. $Na_{(s)}$), and the inclusion of all these in chemical equations such that the law conservation of matter is obeyed. After (Gilbert and Treagust 2009) (p.4)

In view of the of the differences between biology and chemistry, (Treagust and Tsui 2013) produced a four-level model of representation for biology and biology education. They see the four levels to be:

> '(1). The macroscopic level at which biological structures are visible to the naked eye; (2) the cellular or sub-cellular (microscopic) level at which structures are only visible under a light microscope or electron microscope; (3) the molecular (sub-microscopic) level involving DNA, proteins, various biochemicals … (4) the symbolic level that provides explanatory mechanisms of phenomena represented by symbols, formulas, chemical equations, metabolic pathways, numerical calculations, genotypes … etc'(Treagust and Tsui 2013) (p. 8)

The levels used in physics and physics education will be discussed in the forthcoming volume in the 'Models and Modelling in Science Education' series: Treagust, D., Duit, R., Fischer, H. *Multiple Representations in Physics Education.*

There is little doubt that students are all-too-often unable to 'translate' between levels of representation and hence have not acquired meta-representational competence. Cheng and Gilbert (this volume, Chap. 6) outline sources of the particular problems that students have in chemical education. Namely:

- Teachers' use of simplified terms for the macro level e.g. the use of the word 'air' when the active agent in a reaction is 'oxygen';

- The assumption that individual sub-micro representational entities have the same properties as the corresponding macro level;
- The misrepresentation of sub-micro species e.g. the use of Na^+Cl^-, which implied the existence of specific ion pairs at the macro level;
- The failure to use standard terminology e.g. 'NaCl' (the empirical formula) rather than 'sodium chloride';
- Lack of exact knowledge of the complex conventions for the symbolic level as laid down by IUPAC.

It is therefore important that students are systematically introduced to the representational levels used in the sciences, thus acquiring a major manifestation of meta-representational competence. Cheng and Gilbert (this volume, Chap. 6) set out and illustrate a sequence of steps for this to be done i.e.

1. Practical introduction to the macro level;
2. Presentation of and experience with the conventions used in the sub-micro level;
3. Use of the conventions of the sub-micro level to explain properties of the macro level;
4. Presentation of and experience with the symbolic level;
5. Use of the conventions of the symbolic level to explain the sub-micro level;
6. Development of the capability to move between the macro, sub-micro, and symbolic levels, in any order, for a given chemical phenomenon.

14.6.2 Teachers' Use of Visualisations in Teaching

In their paper, Ainsworth and Newton (this volume, Chap. 2) note that relatively little research has been done into teachers' roles when they employ representations in their teaching. A recognition by the editors of this omission was one of the major drives behind the assembly and orchestration of the papers presented in this volume. Ainsworth and Newton (this volume, Chap. 2) provide an effective background to this endeavour by analysing the general significance of representations in science education as reflected in the focuses of the abstracts of research papers and through interviews with teachers. For both these groups, representations were found to be important, although there was a wide diversity in the terminology used for the many perceived types of them. Whilst graphs, diagrams, animations, and text were seen to be important, teachers evidently thought graphs to be less worthy of attention than did researchers. Both groups saw the educational effectiveness, the quality of the design, and the scope for choice, as themes of importance in the actual choice of representations for use in teaching. Echoing established views on the central importance of multiple representations in science and science education e.g. by (Lemke 2004), Ainsworth and Newton (this volume, Chap. 2) noted the value of multiple representations to both researchers and teachers.

This value arises because focus on diverse issues in the provision of effective teaching, for example, when what is wanted is an address to both the problems of understanding met by students and the diversity of their preferences for modes of representation. However, there are commonly severe limitations to the use of multiple, or even just different types of, representations, for a range of reasons.

In their chapter, Eilam, Poyas, Hashimshoni report a study in which they asked serving science teachers: to generate visual representations to be inserted into a diverse range of textual scenarios; to choose the most suitable representation (from a range provided) to accompany a particular piece of text; and finally, at interview, to discuss the reasoning behind their products and choices. There were three major outcomes. First, they found that the semantics of a piece of text resulted in the narrowing of the choice of representational type that teachers felt they could adopt. This narrowing was accentuated where the text was in one language, for example Hebrew, whilst the first language of a particular teacher was different, for example Arabic. These culturally-determined differences have serious implications for teacher education. Second, these issues of the nuances of language are reflected in teachers' ability to write effective captions for representations, thus limiting the educational use that students could make of them. Third, and perhaps most significantly, teachers tended to use a small, simple, and presumably familiar, range of representational types. Of these, the Table was a favoured form, probably because it is socially ubiquitous. However, teachers were often incapable of designing tables that enabled valuable ideas to be perceived. Again, there are implications for teacher education.

From an observation-based study of five biology teachers over a period of 7 months, Liu, Won, Treagust (this volume, Chap. 5) also showed that teachers tend to use forms of visualisation that are both intellectually relatively simple and with which they are evidently very familiar. They drew three general conclusions from their study. First, the teachers tended to mainly use visual representations of the iconic variety – those that were pictures or drawings of concrete objects (Hegarty and Carpenter et al. 1991) – and then largely during the introduction of topics to students, rather than during the subsequent elaboration of those topics, concentrating on the exposition of core concepts rather than on the formation of links between concepts. Second, they made changes between the types of visualisation they use, largely moving on from iconic representations to the corresponding schematic representations – those consisting of abstract imagery (Hegarty and Carpenter et al. 1991) – when providing explanations, but often without justifying that change of use. Third, such changes in type were rendered more complicated, and perhaps more confusing for the students by the extensive use of analogies, many of them created *in vivo* by the teacher. This despite evidence from earlier work that such an approach brings problems in its train, for these' created analogies' are often inappropriate or inaccurate (Treagust and Harrison et al. 1998). Again, it is only through extensive pre-service and in-service teacher education that these limitations to the use of visual representations will be overcome.

14.6.3 Prerequisites to Research-Based Science Teacher Education for Visual Literacy

Before suitable teacher education aimed at visual literacy can take place, additional research is needed. Ainsworth and Newton (this volume, Chap. 2) point to five major areas where more work is needed. First, we know far too little about how science teachers go about the process of deciding what visualisations to use and when to use them. Put another way, we must know more about teachers development and use of pedagogic content knowledge (Shulman 1987) about visualisation. Second, we know far too little about the individual differences of understanding between students in respect of the visualisations with which they are commonly presented. Pedagogic content knowledge can only be deployed if teachers are fully aware of the cognitive status of the students in regard to the content being discussed. Third, we must know more about the effects on students' engagement and motivation of teachers' use of visualisations. We would hope that students would reward a display of meta- representational capability on the part of their teachers by learning more effectively! Four, and looking at matters more broadly, there is a clear need for a meta-analysis of the whole field of research into representation in science education, so that the significance of what is already, known, what comes to be known, and what needs to be known can be properly evaluated. Fifth, and lastly, improvements in science teacher education in respect of representation only take place in teachers are willing to access research and to consider its implications for their practice. As has been shown over many years, getting this is take place is an enduring problem (Levin 2013).

However, all decisions are always taken without complete knowledge of all the factors in operation. So it is with science teacher education for meta-representational competence: we must make the best progress that we can with the knowledge that we have.

14.6.4 Approaches to Science Teacher Education for Meta-representational Competence

It is not appropriate to rehearse successful approaches to mainstream science teacher education, for these have been extensively explored elsewhere e.g. (Gilbert 2010). Sufficient to say that they should be expanded to include both the explicit treatment of visualisation in general (Eilam, Poyas and Hashimshoni) (this volume, Chap. 3) and the planning of suitable teaching activities in particular (Bamberger) (this volume, Chap. 13).

The essence of any such inclusions must be that the teachers have direct experience of the generation and use in teaching of representations produced both by themselves and by their students. This volume includes accounts of four such approaches. First, Parnafes and Trachtenberg-Maslaton (this volume, Chap. 12) report a study in which such in-service education was provided by a teacher requiring school pupils to develop, discuss, and evaluate their own representations, here in respect of the difficult topic of energy. The study concluded that the in-service education that resulted included a substantial shift in the teachers' epistemological beliefs. The second approach reported was based on the consideration by teachers of the educational value of the representations included in 'popular books about science' – those books that, whilst not textbooks, discuss the implications, applications, and technological consequences of science, and which usually include a large number of diverse types of representations (Gilbert and Afonso) (this volume, Chap. 14). The third approach involves expanding teachers' experience and use of interactive simulations -those computer-based representations into which students can enter variables and observe their effects, thus providing support for an inquiry-based approach to science education (Geelan and Fan) (this volume). The fourth approach involves introducing teachers to the creation and use of 'slowmations', 'flip books' of images which show how events in respect of a chosen phenomenon are slowed down such that their relationship to each other can be understood (Loughran) (this volume, Chap. 4).

However, there is one theme, so often overlooked in mainstream science teacher education: the cultural context in which science teaching takes place, that just cannot be ignored when the theme is 'representation'.

14.7 The Cultural Context of Science teachers' Use of Visualisations

Any enduring society develops distinctive ways in explaining the world-as-experienced in order to support the creation of an environment that sustains their way of life. From the fifteenth century and beyond, people in Europe and North America developed that way of explaining the world-as-experienced that came to be called 'science'. It depended on the acceptance of particular beliefs about what knowledge was and how it could be acquired, a distinctive epistemology. This epistemology evolved by assimilating and adapting elements in existing general cultures found there at that time. It was inevitable that such an epistemology formed the basis for the 'science education' that developed over the centuries, first in Europe/North America and more lately throughout the world.

Science education assumes that the students being taught are both familiar with and accept this epistemology. However, the growth of international travel and migration have lead to the circumstance that some, if not many, students is a given class, for example in any capital city, do not meet this criterion. The general cultures from which they come, that of their homes, have produced and continue to use – if only partially – epistemologies that are alternative to those of western science. They will range from simple superstitions e.g. that the position of planets governs patterns in human affairs, to the codified tenets of formal religions e.g. that the dictates of a deity directly governs the actions of everyday life. In general terms, the most clearly delineated forms of such epistemologies are based on: the reliance of non-mechanical entities as the basis for the explanation of phenomena and events; the use of methodologies of enquiry, those on which they depend, that are not available for critical review; the production of little first-hand concrete data, whilst much use being made of hearsay and historical precedent; an ethos of dogmatic assertion by those in valued social positions such that the acceptance of these epistemologies must be based solely on belief; a lack of experimentally verifiable predictions of future events.

Of course, few students in culturally mixed classes will have adopted the most extreme elements of such epistemologies. However, these epistemologies may be present to some degree: indeed, the science teacher may privately concur with some of their tenets. We do not wish to over-emphasise this point, merely to point out that science teaching cannot proceed effectively unless teachers are alert to the possible implications for a cultural non-compatibility between the science curriculum, the science teacher, and the students.

This is a complex issue and one of some delicacy, for an individual's epistemology is very much a part of his/her persona as is their membership of the group from which these ideas are drawn. As such, any tensions in respect of epistemology would be difficult to identify in any great detail.

However, their clearest manifestation is in the chapter by Waldrip, Satupo and Rodie (this volume, Chap. 8) who, in science classes in Melanesia and Indonesia, found the issue to come up in a variety of ways. To take two examples. First, whether a teacher was male or female had a major impact of the acceptance of ideas about visualisation that she/he put forward. The valuation of ideas independent of the identity of the proposer, a major tenet of orthodox nature of science, was not seen in this case. Second, the social status of individual students, as ascribed by their membership of a particular ethnic group, had a major impact on the nature of the consideration given to their ideas. Ideas produced by 'low status' students were derided or ignored. Indeed, major differences over epistemology can exist in countries with very different cultural backgrounds, as de Vries and Ashraf (this volume, Chap. 7) discuss in respect of the types of representations that are used in France and in Pakistan.

It is hoped that this volume will help focus attention on the importance of MRC in the learning of science and hence the pressing need for it to be given a higher saliency in science education at all levels. In particular, by having emphasised what is already known about MRC, researchers will be encouraged to fill the important gaps in existing knowledge and to introduce the theme into teacher education.

References

diSessa, A., & Sherin, B. (2000). Meta-representation: An introduction. *Mathematical Behaviour, 19*, 385–398.

Gilbert, K. (2008). Visualisation: An emergent field of practice and enquiry in science education. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualisation: Theory and practice in science education* (pp. 3–24). Dordrecht: Springer.

Gilbert, J. K. (2010). Supporting the development of effective science teachers. In J. Osborne & J. Dillon (Eds.), *Good practice in science teaching* (pp. 274–300). Maidenhead: Open University Press.

Gilbert, J. K., & Treagust, D. F. (Eds.). (2009). *Multiple representations in chemical education*. Dordrecht: Springer.

Hegarty, M., Carpenter, P., et al. (1991). Diagrams in the comprehension of scientific texts. In R. K. Barr (Ed.), *Handbook of reading research* (pp. 641–668). New York: Longman.

IUPAC. (2013). *IUPAC compendium of chemical terminology: The gold book*. Washington, DC: IUPAC.

Johnstone, A. (1993). The development of chemistry teaching: A changing response to a changing demand. *Journal of Chemical Education, 70*(9), 701–705.

Lemke, J. (2004). The literacies of science. In E. W. Saul (Ed.), *Crossing borders in literacy and science instruction: Perspectives on theory and practice* (pp. 33–47). Newark: International Reading Association.

Levin, B. (2013). To know is not enough: Research knowledge and its use. *Review of Education, 1*(1), 2–31.

Paivio, A. (1986). *Mental representations: A dual coding approach*. New York: Oxford University Press.

Pearsall, J. E. (1999). *The concise Oxford dictionary*. Oxford: Oxford University Press.

Pierce, C. (1931). Logic as semiotics: The theory of signs. In B. Justus (Ed.), *Philosophical writings of piece (1893–1910)* (pp. 98–119). New York: Dover, Reprint 1955.

Shulman, L. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review, 57*(1), 1–22.

Treagust, D., & Tsui, C. Y. (Eds.). (2013). *Multiple representations in biological education*. Dordrecht: Springer.

Treagust, D., Harrison, A., et al. (1998). Teaching science effectively with analogies: An approach for pre-service and inservice teacher education. *Journal of Science Teacher Education, 92*(2), 85–101.

Van den Akker, J. (1998). The science curriculum: Between ideals and outcomes. In B. F. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (pp. 421–448). Dordrecht: Kluwer.

Vygotsky, L. (1978). *Mind in society: The development of higher psychological processes*. Cambridge, MA: Harvard University Press.

Vygotsky, L. (1986). *Thought and language*. Cambridge, MA: MIT Press.

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