Chapter 12
The Application of a 'Model of Modelling' to Illustrate the Importance of Metavisualisation in Respect of the Three Types of Representation

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Abstract The value of models, modelling and visualisation as a basis for developing an understanding of the nature of and the relations between the three levels of representation is discussed. The requirement for and problems in the development of metavisualisation (a fluent capability in visualisation) are presented. Student practical work, closely associated with teacher questioning, is advocated as a way of developing these skills. A 'Model of Modelling' is presented. In order to validate this model, it was applied to the teaching of 'chemical equilibrium', this being a very important topic for which student misconceptions are well documented. Data were collected from six lessons in which the model was applied excessively with respect to the nitrogen dioxide/dinitrogen tetroxide and chromate/dichromate systems. Students developed a good understanding of chemical equilibrium, as shown by the absence of common misconceptions in an end-of-course attainment test. Students acquired an appreciation of the relationship between the three levels of representation. The value of the model of modelling, with its associated pedagogy as a support for the acquisition and use of metavisual capability, was established.

Introduction

Being able to readily switch the focus of thinking between the macro, the sub-micro and the symbolic levels of representation is a core capability for any competent chemist. This status derives from the fact that chemistry is concerned with the transformation of matter at the atomic level. Chemists start their work by either selecting or creating an apparently simple example of the phenomenon in which they are interested. What they can see and manipulate constitutes the macro level of the phenomenon. As chemistry (like all the sciences) is concerned with the production of explanations for observed phenomena, they then try to imagine why the phenomenon behaves as it does. The products of this imagination, tested for validity by the making and testing of predictions about the behaviour of the phenomenon under different circumstances, are at the sub-micro level. Chemistry, again like all the

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sciences, advances by progressively producing ever-more convincing explanations for broader sweeps of phenomena. This advance always includes attempts to quantify what exists or is taking place: this leads to the symbolic level. In short, knowing about the three levels enables the bulk properties, the qualitative explanation of those properties, and the quantitative explanation of them, all to be understood. Moving between these levels enables them to be readily related to each other. It also exemplifies scientific methodology.

Students all too often find this capacity difficult to acquire (Johnstone, 1982). For example, Hinton & Nakhleh (1999) found that a sample of undergraduate students in the USA were able to mentally operate at the macro and symbolic levels, yet had difficulty linking these to the equivalent representations at the sub-micro level. Another study (Treagust, Chittleborough, & Mamiala, 2003) investigated the way that Australian students use sub-microscopic and symbolic representations when providing explanations for chemical phenomena. According to the authors, students' explanations of a given phenomenon were influenced by their ability to recognise different representation forms of that phenomenon and to transfer from one level of representation to another. Kozma & Russell (1997), when investigating expert chemists' and novice students' understanding of various forms of representation, showed that the experts were much better than novices in transforming one mode of representation into another. This facility is a major contribution to the notion of 'expertise' in chemistry.

Studies like the ones briefly commented on above provide evidence that, in order to develop their chemical knowledge, students must know how to use the three levels of representation, how to express such knowledge in different modes of representation, and how to transfer one representation into another when this were necessary to the understanding of particular aspects of a phenomenon. We suggest that if an efficient, effective and economical, general approach to the development of 'three-level fluency' is to be established, it must be based on a cognitive model embedded within a sound view of the nature of science. Such an approach might therefore be based on the notions of models, modelling and visualisation.

A model is one of the main outcomes of any scientific enquiry and hence is a major contributor to philosophy of science. A model may be defined as a simplified representation of a phenomenon (an object, system, event, process) or idea produced for the specific purpose of providing an explanation of that entity, the most important outcomes of which are the production of successful predictions of how it will behave under a range of circumstances (Gilbert, Boulter, & Elmer, 2000). Entities can be modelled at the three levels: at the macroscopic, by representing some of the aspects of the entity that can be seen; at the sub-microscopic, by representing the ideas produced to explain the constitution and behaviour of the particles that constitute the entity; and at the symbolic, by representing the symbols created to simplify the reference to such particles (as, for instance, chemical formulae and chemical equations).

A model is always initially produced in a person's mind – being then called a *mental model*. For communications purposes, it must be expressed in different modes of representation: concrete, verbal, mathematical, visual, gestural or mixtures of these – some of them being static and others dynamic (Boulter & Buckley, 2000). There is not a restricted correspondence between the level of the entity that is being modelled and the mode of representation used to model it. Aspects of the macro and sub-micro levels can be expressed in all the modes of representation, whilst aspects of the symbolic level are generally expressed as in the verbal or mathematical modes. This indicates the importance of the use of the modes of representation in a comprehensive understanding of the three levels in which a given entity can be modelled.

The understanding that a mental model makes possible is a *visualisation* of its structure and behaviour. For instance, a mental model of a phenomenon makes it possible to predict, by means of visualisation, how it might behave in different circumstances. When a scientist places a mental model in the public arena by means of one or more of several modes of representation, s/he is providing an *external representation* of that model. The *internal representation* that another person forms from this is the mental model for that person. One great ambition of science education is that all students’ internal representations of a given model will be very nearly the same as the corresponding external representation. This corroborates the special attention given to how students express their models for entities at different levels. In chemistry teaching, in particular, this issue assumes a major relevance because, as most models represent abstract entities, their visualisation must be an essential part of students’ understanding. One of the ways to support the exercise of such visualisations is to provide students with opportunities to create and express their own models, namely to involve them in a modelling-based approaches to teaching.

Modelling, defined as the dynamic process of producing, testing, and revising a model, is a core skill in scientific enquiry. Authentic science education, that which is based as closely as possible on scientific practice as educational circumstances will allow, must therefore include the development of the skills of modelling. We suggest that, by facilitating the development by students of personal mental models of each of the three levels of representation and by encouraging them to mentally ‘move’ between these, they will acquire the core skill mentioned above. This fluent performance in visualisation has been described as requiring and demonstrating *metavisualisation*, namely the ability to acquire, monitor, integrate and extend learning that involves both internal and external representations (Gilbert, 2005). More specifically, metavisualisation involves the demonstration of five capabilities in a wide range of contexts. These are:

1. *Understanding of the ‘conventions of representation’* for all the modes and submodes of representation involving all three dimensions that are commonly used in science: One dimension, the use of chemical and mathematical symbols (for these can be regarded as point objects); two dimensions, the use of pictures, graphs and diagrams of all types; three dimensions, the use of material or concrete forms. That is, how these relate to the model being represented and to the representational scope and limitations that ensue;
2. *The capacity to mentally ‘translate’ a given model between the modes and submodes and between the levels of representation in which it can be depicted.* In so

doing, they will be able to move between the three levels of representation. For example, being able to relate representations of the bulk properties (the macro level), the physical behaviour of individual particles (the sub-micro level), and the statistical behaviour of the properties of these entities as a whole (the symbolic level), of the 'particulate nature of matter' to each other, especially in the gas phase;

3. *The capacity to construct a representation in any appropriate mode and sub-mode for a given purpose*. For example, being able to represent the working of an oil refinery in terms of a diagram of its component parts to an explanation of what takes place in terms of molecular transformations and the chemical equations for these;
4. *The capacity to use visualisation as the basis for the construction of predictions of behaviour in respect of a given model*. For example, being able to visualize the sub-microscopic structure of an ionic crystal so as to predict how it will cleave when subjected to an external force;
5. *The capacity to solve novel problems by constructing analogies to already-used visualisations*. (Gilbert, 2008). For example, using Kepler's model of the Solar System to explain the electronic structure of an atom, in the manner of Bohr, and hence being able to predict, very approximately, the absorption spectrum that it will produce.

In an overview of existing research (Ainsworth, 2008), it has been shown that students have a wide variety of problems in generating and using representations consistently and coherently, particularly when several have to be retrieved/constructed in a given context. Thus, they do not: understand all the nuances of many of the major conventions of representation, let alone the sub-conventions which exist within each of these; grasp the relationship between any given representation and the phenomenon to which it applies; have criteria by means of which to select a representation that is appropriate for a given purpose; understand how to construct an appropriate representation; readily relate different representations of a given phenomenon to each other. In short, research has shown that, for many students, metavisual capability is a difficult skill to acquire.

The nature of these challenges suggests that practical work, allied to a suitable use of cognitive theory and philosophy of science, may be helpful in meeting them. Although practical work by students may have many purposes (Bennett, 2003), its educational value in general is too often hindered by confusion, in respect of any specific practical activity, about which of these purposes is being addressed (Hodson, 1990). Inevitably, the development of the skills of visualisation would be hindered, rather than helped, by practical work for which the purpose was not clear to the students.

Consequently, practical work that may be more successful in supporting the development of metavisual capability would pay explicit attention to

- focusing on those aspects of a phenomenon under study that require explanation provided through sub-microscopic and symbolic representations;

- showing how science provides explanations of progressively increasing insight that apply to ever-more complex examples of a phenomenon;
- appreciating that external representations at the macro level have a distinct and probably only partial relationship to the world-as-experienced;
- showing students that macro-level representations provide them with an entry point to the exploration of the world-as-experienced;
- helping students to generate questions, based on external representations at the macro-level, such that their perceptions of the world-as-experienced are enhanced.

In this chapter, we present an attempt to put these ideas into practice that has three components. First, we use a 'Model of Modelling', an external representation of the mental processes that we postulate to be undergone as a person forms a model. Second, this model is exemplified by its application to the design of a teaching sequence about a key topic in chemistry, the understanding of which requires fluency of mental movement between the three levels of representation. Lastly, this application is implemented in such a way that the processes of students' thought taking place can be monitored.

A Model of Modelling

Several researchers (for instance, Morgan & Morrison, 1999) have recognised that there is no such thing as a unique way to produce models. However, other researchers have discussed the general steps by which they are produced (Clement, 1990; Halloun, 2004). Justi & Gilbert (2002) have produced a 'Model of Modelling' framework (Fig. 12.1).

Modelling is represented within this framework as a non-linear process comprising multiple stages, as follows: *Stage 1* ('Decide on purpose' and 'Have experience'): after the definition of the aim(s) of the model (i.e. what it is to explain), it is necessary to acquire information about the entity that is being modelled (from empirical observations and/or from previous knowledge). *Stage* 2 ('Produce a mental model'): a mental model is constructed from the information acquired by the selection of an adequate source for the model (something from which an analogy could be proposed) and the use of creativity and reasoning. *Stage 3* ('Express in mode(s) of representation'): this involves the selection of an appropriate mode of representation with which to produce the expressed model. *Stage 4* ('Conduct thought experiments'): with the mental model created and suitably expressed, the initial testing stage always has a mental phase (known as thought experimentation) which may prove decisive in the evaluation of the model. *Stage* 5 ('Design and perform empirical tests'): where the processes involved in Stage 4 are successful, empirical experimentation is designed and carried out, provided that the entities involved are amenable to such treatment and if suitable resources exist. Then follows either *Stage 6* ('Fulfil purpose'): if the model proved to be successful (in terms of its defined purpose), its 'scope and limitations can then be considered. If Stage 4

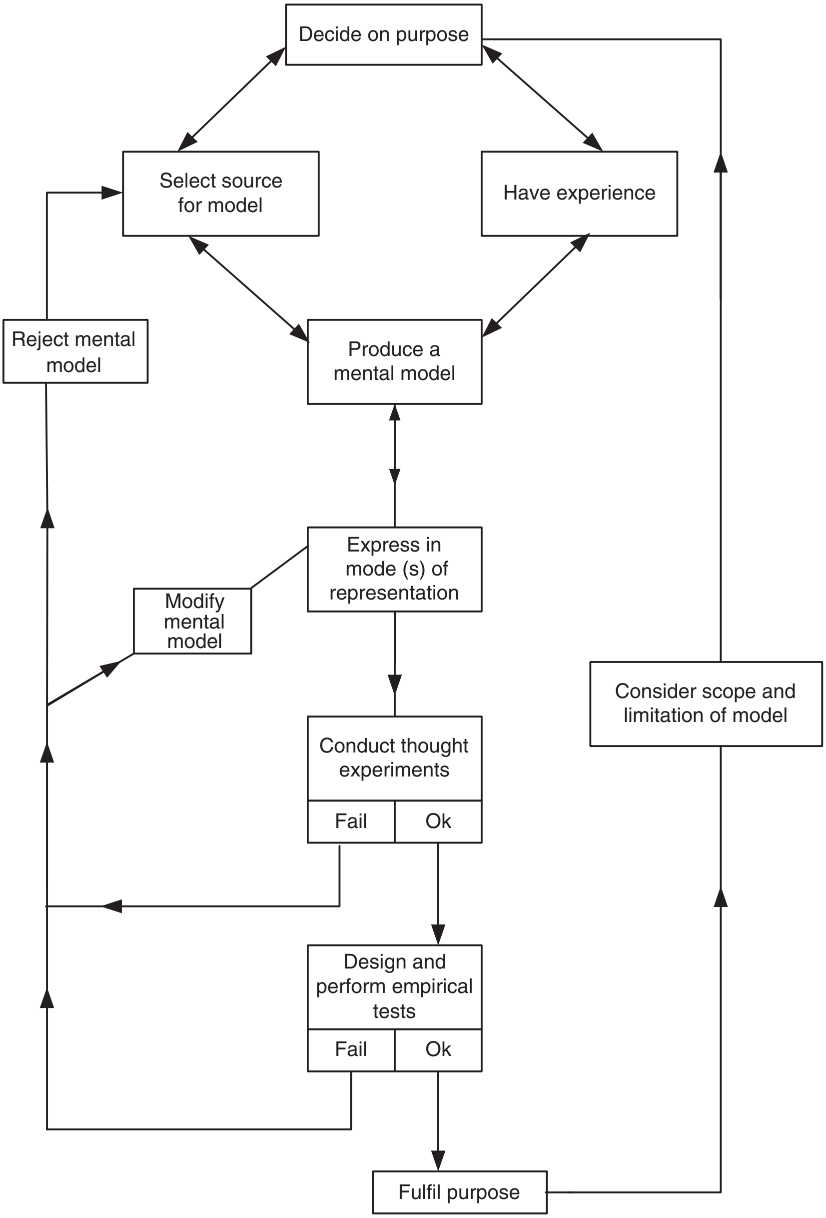

Fig. 12.1 The 'Model of Modelling' framework (Justi & Gilbert, 2002, p. 371)

or Stage 5 are unsuccessful, due to the incapability of the model either to explain a given aspect of the phenomenon or to the inadequacy of a prediction made, then *Stage 7* ('modify or reject mental model') follows: the model must be altered or a completely new model proposed.

The 'Model of Modelling' framework has been used in science teaching in the production of modelling-based teaching activities (for more details, see, for instance Ferreira & Justi, 2005; Justi, 2006; Justi & Mendonça, 2007; Mendonça & Justi, 2005). Essentially, modelling-based teaching consists of lessons framed by the 'Model of Modelling' and consisting of activities to support an address to each of the Stages in that model. Such teaching includes the following *pedagogical elements*: gaining empirical evidence; asking, provoking and answering questions; identifying students' previous ideas; encouraging the expression of models in suitable modes of representation; facilitating discussions about the models and their modes and levels of representation. Our studies have shown that the engagement of students in this kind of activity contributes to more meaningful and participative learning, particularly manifest in an improved ability to comprehend and mentally move between the three levels of representation. This mental process takes place because, in the contexts of these teaching activities, students have the opportunity to experience the interest and excitement of the stages in the production of scientific knowledge, to think about the purposes of science, to create explanations and predictions, to analyse different situations that may result in a need for modifying their initial model. This model has been applied to the topic of 'chemical equilibrium'. First we present some background about this topic.

Learning About Chemical Equilibrium

The notion of 'chemical equilibrium' is central to an understanding of the nature of chemical reactions. An understanding of it involves an appreciation that

- all reactions must be viewed, at least in theory, as being 'incomplete', with an equilibrium existing between the concentrations of the reactants and the products;
- when started, the rate of the forward reaction is high but decreases with time as the concentration of the reactants decreases whilst, over the same period of time, the rate of the reverse reaction increases as the concentration of the products increases. At equilibrium, the two are equal;
- changing the conditions of either the forward or reverse reaction causes the extent of the reactions to change until the equilibrium is re-established.

In terms of levels, understanding the notion of 'chemical equilibrium' involves being able to mentally 'translate' between: the macro level, conceived in terms of the observable properties (e.g. colour); the sub-micro level, conceived as being identities of the specific species involved and their associated behaviour; the symbolic level, this involving being able to both manipulate and understand the 'equilibrium equation', as well as other representations of the process (e.g. graphics).

An excellent overview of the problems that students experience in learning the notions underlying 'chemical equilibrium' is available (van Driel & Graber, 2002). Research shows that conceptual problems arose when students, who had been introduced to chemical reactions through examples that evidently go 'to completion', first met examples of 'incomplete reactions'. In this situation, they

- were often unable to discriminate between reactions that 'go to completion' and those that do not;
- believed that the forward reaction goes to completion before the reverse reaction commences;
- failed to discriminate between the rate and extent of a reaction;
- believed that the rates of both the forward and reverse reaction increase with time until equilibrium is reached.

At a later stage in their science education, presumably after they had been taught about 'chemical equilibrium', older students

- either did not understand the dynamic nature of the equilibrated state or perceived it to be an oscillation between the existence of only reactants and only products;
- had a compartmentalised view, seeing the forward and reverse reactions as acting independently of each other;
- believed that 'mass' and 'concentration' mean the same thing for substances in equilibrium systems;
- believed that the concentrations of the reactants and products were always equal at equilibrium.

In our view, such students' difficulties as described above originate, mainly, from a failure to recognise and teach chemical equilibrium as a *process*. These problems are the outcome of a quantitative approach being taken to the theme to the detriment of understanding chemical equilibrium qualitatively. As a consequence, students have difficulty understanding these and other issues in terms of Le Chatelier's Principle, which demands knowledge about how the processes occur.

Using the 'Model of Modelling' in the Teaching of Chemical Equilibrium

From the 'Model of Modelling' framework and knowledge of students' difficulties in learning chemical equilibrium, we developed a modelling-based teaching sequence for this theme (Ferreira & Justi, 2005). The sequence provides students with opportunities to build, test and rebuild models in order to explain: the occurrence of a given chemical reaction, the reversibility of that chemical reaction, the establishment of a chemical equilibrium in the system under study and the behaviour of the system when the equilibrium is changed. The students were not directly introduced to the modelling framework, but were provided with conditions for developing each of the above-mentioned stages. These stages involved identifying students' previous knowledge – about both models and modelling and how chemical reactions occurs (in terms of the kinetic particle model) – and the establishment of relationships between such knowledge and the new empirical and theoretical data acquired through the activities provided. In brief, students were involved in the following activities:

Activity 1: Discussing what was to be done (including the fact that the sequence of lessons formed part of a research project), discussing the nature and purposes of models, identifying and developing students' ideas about modelling. In terms of the 'Model of Modelling' this involved 'having experience' in everyday life (Stage 1).

Activity 2: Identifying students' previous ideas about the nature of chemical reaction, building a model for how the transformation of one system in equilibrium – dinitrogen tetroxide (N_2O_4) and nitrogen dioxide (NO_2) – takes place from empirical observations of the system, building a model for how the reverse transformation occurs from these observations, building a model for the system at room temperature. The main aims were to support the development of students' ideas about the reversibility of chemical reactions – an aspect that was not part of their previous knowledge – and to support the creation of a first model for the equilibrium situation by considering the co-existence of the two species and the dynamics involved. In terms of the 'Model of Modelling', this involved 'having experience' (Stage 1), 'selecting a source for the model', 'producing a mental model' (Stage 2) and 'expressing that model in a suitable mode of representation' (Stage 3).

Activity 3: Conducting an empirical experiment to observe the transformation of CrO_4^{2-} (chromate ion) into $Cr_2O_7^{2-}$ (dichromate ion), collecting evidence of the presence of both chemical species in the system at any time, building a model to explain the behaviour of the system. In terms of the 'Model of Modelling', this involved 'conducting thought experiments' (Stage 4), 'modifying mental model' (Stage 7), and 'expressing the new model in a suitable mode of representation' (Stage 3) for those students who had been able to produce a model including the reversibility in the previous activity. For the other students, this activity involved 'having experience' (Stage 1) of another specific reaction, 'producing a mental model' (Stage 2) and 'expressing it in a suitable mode of representation' (Stage 3). In both cases, in doing so, students extended their ideas about the processes occurring in and the reversibility of a chemical reaction.

Activity 4: Conducting an empirical experiment to observe both what happened when the equilibrium between CrO_4^{2-} and $Cr_2O_7^{2-}$ was modified by adding acid or basic solutions, thus collecting evidence of the presence of both chemical species in the system at any time. This activity led to the use of the previous model to explain what happens when the equilibrium was changed. In terms of the 'Model of Modelling', this involved 'considering scope and limitations of model' (for students who had thought about reversibility since Activity 2; Stage 6), or 'modifying mental model' (Stage 7), and 'expressing the new model in a suitable mode of representation' (for students who had not included the reversibility idea in their models in the previous activity; Stages 2 and 3).

Activity 5: Discussing the relationships between the two systems studied, building a class consensus model for chemical equilibrium, discussing characteristics of such a model, evaluating the teaching approach that had been adopted. Methodologically, the main aim of this activity was to organise all the ideas that students had developed about chemical equilibrium (in essence, to address Stages 1–6 at the same time).

Activity 6: Identifying students' ideas about chemical equilibrium at the end of the above sequence of activities. This task was accomplished through a questionnaire.

Investigating Students' Understanding of the Types of Representation

Aims and Research Questions

The above six teaching activities, used in an ordinary educational context, were investigated in order to probe the influence of the modelling activities on students' learning (Ferreira, 2006). Two research questions guide the current discussion:

1. How did the pedagogical elements provided in support of the modelling-based teaching activities contribute to the development of understanding about the levels of representation, thus to the learning of the nature of chemical equilibrium?
2. What capability did the students have both to visualize the three levels of representation and to move between them, during this modelling-based teaching?

Data Gathering

The use of the modelling-based strategy above described was investigated from an action research perspective by one of us (PF) who was the chemistry teacher of a first grade medium level school class of 26 students (14–15 years old) in Brazil.

Data were gathered during activities described in the six lessons of 100 minutes. In Activities 1–5 (in consecutive lessons) students worked in groups (4–6 students), while in Activity 6 (some weeks later) students worked individually. This teaching approach was adopted to promote students' understanding of how a chemical equilibrium process occurs by supporting the use of empirical observation and discussion (guided by relevant generative questions[1]) of aspects related to the dynamic nature of a chemically equilibrated state – something that is not apparently common in traditional teaching approaches.

Data were gathered from written material produced by the students during the whole process (including the final questionnaire, the video recording of all lessons, and audio recording of the discussions of each group of students).

Data Analysis

Data gathered in the lessons were used to produce case studies for each of the groups of students because such case studies yield rich descriptions of events that are presented in a chronological narrative that incorporates the researcher's observations. Due to the possible inclusion of such an interpretation of the data, case studies go beyond simple descriptions of the situation and support the analysis of the phenomenon being studied (Cohen, Manion, & Morrison, 2000). In order to discuss the research questions, we browsed the original case studies to identify evidence of how the students dealt with the levels of representation. Whenever it is appropriate, such evidence is included in the later sections of this chapter.

In order to assure the internal validity of the data analysis, two of the authors (RJ and PF) analysed the original case studies (that are written in Portuguese) independently. The results were compared and any disagreement was discussed and resolved. Then all the relevant evidence was translated into English to be discussed with the third author (JG).

Results

The analysis of the case studies showed how students constructed their representations, as well as identified the specific contributions that these representations made to the production of students' knowledge. Representative examples of both aspects were selected from the case studies.

The Research Questions

In order to organise our discussion, the results are presented separately for each of the research questions. However, due to the emphases being adopted here, we

[1] According to Vosniadou (2002), generative questions are those that "cannot be answered on the basis of stored information but require the genuine solution of a new problem." Therefore, in order to answer a generative question, the subject "must create a mental representation or a mental model" of the entity "and explore it in order to derive from it a relevant answer" (Vosniadou, 2002, p. 358).

decided to include specific aspects of the discussion, and actual examples of students' thoughts and drawings in the context of the second research question.

Research Question 1: How did the pedagogical elements provided in support of the modelling-based teaching activities contribute to the development of understanding about the levels of representation, thus to the learning of the nature of chemical equilibrium?

In order to address this research question, we browsed the original case studies to identify evidence of how the students dealt with the levels of representation and of any possible relationship between such students' activities and any of the elements of the modelling-based teaching. In the following discussion, the most relevant elements of this teaching are emphasised.

We found that the motivation for students' participation in the process of developing their understanding arose from the **empirical evidence** they acquired (from the two initial Activities and those related to the transformation NO_2/N_2O_4) and from the initial challenge to model how the transformation occurred under different temperature conditions. Such models were simple ones because they could be produced only from their interpretations of the empirical evidence together with their previous knowledge. In principle, students could have produced models to represent the process by using the three levels of representation (macroscopic, sub-microscopic and symbolic) in the abstract. However, they had been asked to produce a model that could explain *how* the process occurs, which means that they should propose a sub-microscopic representation. As this question could *not* be answered with the use of students' prior knowledge, the role of experimental evidence was, mainly, to challenge the students to build new knowledge.

The system NO_2/N_2O_4 was used to provide a gradual presentation of new elements that should be incorporated into their models. As students analysed the macroscopic changes of the system, they proposed a series of changes to their previous representations. The observation of the system for the second time (when it was warmed) was crucial for thinking about the possibility of the occurrence of reversibility in the system (since until then the students had dealt only with chemical reactions that occurred in one direction). During the discussion, the equations for both transformations ($2NO_2 \rightarrow N_2O_4$ and $N_2O_4 \rightarrow 2NO_2$) were written at the board by the teacher. This means that students also had access to representations at the symbolic level (at an appropriate moment), which they could integrate into their observations of the empirical systems in producing and representing their models.

The observation of the system NO_2/N_2O_4 provided essential empirical evidence to support the idea that the reactant and product could coexist. According to the questions posed in the activity, this evidence could not only be made explicit in the representation of their models but also be explained by the models. The students who were able to establish relationships between the movement of molecules and the occurrence of a chemical reaction (according to the kinetic particle model that had been studied earlier), were also able to include dynamic components in their models. Those who were not able to do so had the opportunity to think about this from the general discussion of the models – when all groups presented and justified their ideas – or from other empirical evidence that was obtained next.

The system CrO_4^{2-} / $Cr_2O_7^{2-}$ provided students with a new context within which to use the model previously created for the system NO_2/N_2O_4. From this second system students (i) acquired additional evidence about the coexistence of reactants and products in a chemical reaction and (ii) could observe what happened when the equilibrium was changed. This last set of empirical evidence was included in the teaching activities specifically to support the testing of students' previous models.

One of the differences between the two empirical systems was the complexity of the particles involved in the reactions. As in the previous case, the teacher provided students with the formulae of the species involved and, at an appropriate moment during the discussion of this system, she also wrote the equation $2CrO_4^{2-} + 2H^+ \rightarrow Cr_2O_7^{2-} + H_2O$ on the board. When students tried to use their previous models to explain this system, they found that they had to represent more complex structures. However, this change did not present a difficulty to most of them. On the contrary, the students used the information that the species participating in the second system had more atoms than in the first one to propose interesting mechanisms for the occurrence of the reaction. (More details are presented in the discussion of the second research question.) The concrete representation of the species had an essential role in the production and testing of their models.

In sum, the empirical evidence presented new information about the systems under study, prompting the creation of new expectations concerning the models previously built, and encouraging students to think about the applicability of both the model itself and its modes of representation. These considerations often resulted in a changing of the models in a way as to widen their scope of application to new contexts.

Another element of the modelling-based teaching that was relevant for the development of students' ideas was **the teacher's questioning**. Most of the time, this occurred during a discussion between the teacher and a specific group of students. In these cases, the teacher tried to take into account those students' previous knowledge, models and doubts. At other times, the teacher's questions were posed to the whole class as she tried to motivate them to think about different explanations – or more complete ones – in order to support the testing of their models. Very frequently, these questions facilitated students' expression of the codes that were used in their representations, thus allowing for a more comprehensive understanding of both the modelling process in general and the process of building a given representation in particular.

The way that the teacher conducted the lessons contributed to making some details of the systems explicit and helped students in interpreting (i) the empirical evidence, (ii) the questions to be answered by the models, and (iii) the symbolic representations she presented for each system. Moreover, the teacher's questions supported the students as they tried to remember previous ideas and/or models, to identify the limitations of their models, to propose new models or new explanations for the use of their models in new contexts. Finally, the teachers' questions were very helpful for increasing students' confidence in their models.

One of the important elements of the 'Model of Modelling' framework is the consideration of the subject's previous ideas as one of the 'experiences' needed to support the proposition of the mental model. In this teaching situation, **students' previous ideas**, mainly those related to the kinetic particle model, were essential to the inclusion of fundamental attributes in their models (e.g., the dynamicity of the chemical transformation).

The **expression of the models** in different modes of representation occurred during the whole process and, as has been previously commented upon, exerted an essential role in the development of students' knowledge. This was particularly relevant for those students who could understand the relevance of the choice of a given code and level of representation in order to better express the mental model previously produced. In several activities, students were asked to propose a concrete model for a specific system. This was shown to be essential for the development of students' ideas because, from the concrete models, they could produce simulations of the chemical process and think about details related to the mechanism of the chemical reactions (such as the directions of the necessary collisions between the molecules, something that they had not studied before).

The **discussion of the models** by the whole class was another element of the teaching process that contributed to students' learning. During and/or from the general discussion of the models, students could (i) think more deeply about their own models in order to be able to answer the teacher's and their colleagues' questions, (ii) share some doubts, (iii) integrate some of their colleagues' ideas into their models and (iv) appreciate the limitations of their own concrete representations as ways of expressing their mental models.

The aspects previously discussed support the assertion that specific Stages of the modelling-based teaching and the pedagogical elements of support for those Stages both influenced the students' learning. Alas, inevitably not all students were found to have a clear understanding about all the attributes of the qualitative curricular model they were expected to acquire in the lessons. The models produced by the different groups of students presented particularities that differentiated one from another and which were apparently constructed using different reasoning processes. But we have evidence that, for most of the students, the engagement in the process of producing, expressing, testing, changing their own models, and applying them in different contexts, contributed to a good understanding about how the process of chemical equilibrium occurs in a system. Thus, from their answers to the final questionnaire, we realised that all students understood that a chemical equilibrium is a dynamic process that is established when the velocity of the forward and of the reverse reactions become equal, thus resulting in a coexistence of reactant and product species in the system. No student expressed any of the alternative conceptions related to these elements of the model described in the literature and reviewed earlier in this chapter. The only difficulty some of the students found was in explaining what happens in a chemically equilibrated system when one of the conditions (temperature or concentration of one of the species) is changed. In our view, this could have been the result of two factors (or a combination of them): this specific issue is a complex one and was discussed only in the last class, there perhaps being too little time available; the level of participation of the students in the discussions (with their colleagues in group and with the whole class) was not homogeneous – some did not participate verbally.

In sum, the analysis of the students' learning process showed how each of the elements of the modelling-based teaching (previous ideas, empirical evidence, expression of models, questions, discussions about the models and their modes and levels of representation, etc) contributed to a meaningful learning of the main attributes of a qualitative model for chemical equilibrium. This allowed students to understand the process at the sub-microscopic level and for this to be associated with both the interpretation of the macroscopic evidence and with the use and understanding of adequate symbolic representations. The analysis also provides evidence that each of the Stages and Elements in the modelling-based teaching influenced the development of specific ideas in an idiosyncratic way for each group of students. This corroborates our belief that the dynamic and non-linear process of learning science (particularly chemistry) can be viewed – and fostered – as a process of the successive building and rebuilding of models by the students.

Research Question 2: What capability did the students have both to visualise the three levels of representation and to move between them during this modelling-based teaching?

The data provided the following evidence for the acquisition / deployment of metavisual skills in trans-level migration:

(i) *Mental modelling preceded external representation*: The students were all initially concerned with the building of a mental model. Some groups spent a lot of time discussing their ideas without writing anything or using any concrete materials. However, in all groups, as soon as one student started to make his/her ideas visible, all the other members either continued using that mode of representation or sought a different, better, one. When building the models for the latter system studied, some groups paid special attention to producing an adequate expression of their mental models. During the process of communicating and discussing their models, students realised that the way a model is expressed may change its meaning.

(ii) *External representations were not assumed to be copies of the macro system*: None of the students tried to produce their concrete models for the sub-micro level by using visual characteristics of the macro system. In particular, they used play-dough of colours that were different to those of the macro systems to represent their molecules. In one of the student groups, their written responses emphasised that 'the colour of the system is a consequence of the interactions between molecules; there is no colour for a single molecule'.

(iii) *Different components of various levels of representation were introduced into their models to justify changes occurring at the macro level and explained at the sub-micro level*: Changes in the system observed when the temperature of the NO_2/N_2O_4 system varied were justified in terms of kinetic energy of the molecules. One of the groups used 'movement' symbols to emphasise such differences when they drew their concrete model in the worksheet (Fig. 12.2).

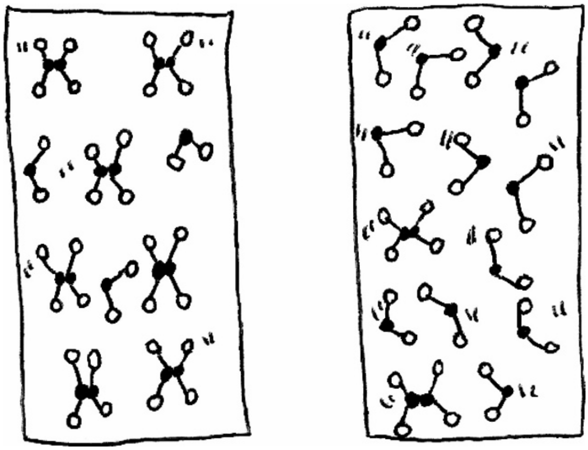

Fig. 12.2 Drawing of the model for explaining the occurrence of the transformation of N_2O_4 into NO_2

Such students explain their model by saying that

> At the beginning of the reaction, molecules have a small kinetic energy that is not enough to break the nitrogen bonds. When the system receives energy, the molecules became more agitated and the bonds between the nitrogen atoms are broken, thus producing NO_2.

(iv) *The role of the symbolic level in the modelling process varied for different students and at different times of the process*: When the data were collected, the students had not yet studied chemical bonding. But they knew the general meaning of symbols and formulas. Therefore, they had no problems in understanding the meaning of N_2O_4 and NO_2 when the teacher wrote them on the board. However, the way the students translated this symbolic representation into other levels changed at different stages of the modelling process. Initially all of them used balls to represent atoms in the correct proportions. Only some of them used sticks to represent bonds. In both cases, they found it very helpful to produce their models from the information obtained from the symbolic model because it made it easier for them to 'see' what was necessary to happen in order to transform one substance into another. Later on, when they were asked to model the system CrO_4^{2-} / $Cr_2O_7^{2-}$, and were faced with the complexity of the structures, one of the groups decided to use only one ball to represent the CrO_4^{2-} ion and a different one to represent the $Cr_2O_7^{2-}$ ion. Being supported by their knowledge about the purposes of models, they justified their choice:

> We produced a single model because here what we want to make evident is the coexistence of the species, nor how one was transformed into another.

When they were challenged by another group to really explain the occurrence of the transformation, they constructed more than one ball and stick representations for each species in order to support the production of their model. Moreover, the students discussed their colleagues' models, making it evident that they had understood other models of representation.

(v) *Explanations were developed by moving between the macro and the sub-micro levels*: In Activity 2, when asked to produce a model for the NO_2 / N_2O_4 initial transformation, all students produced concrete representations of the sub-micro level. However, whilst discussing in groups, some students produced iconic depictions of the phenomena itself, i.e. they drew the initial and the final macro systems showing their different colours. When arguing about the systems with their colleagues, such students pointed to their drawings (rather than to the macro system). However, their discussions were focused on the particles in those systems. Apparently, the students used such drawings as a way to organise the data that they were thinking about. This action shows the importance of empirical evidence in the modelling process.
It should be noted that this kind of drawing (representing the macro level) was done only for the N_2O_4 / NO_2 system. Moreover, it was only used to represent the macro level in the situation above described.

(vi) *Explanations were produced simultaneously at the macro and sub-micro levels*: Later in Activity 2, when the students had observed both the transformations (N_2O_4 into NO_2 and NO_2 into N_2O_4), as well as the system at room temperature, and were asked to produce a model to explain the intermediate colour of the latter system, one group drew beakers with hot and of cold water, both holding a tube containing the gases. They also produced concrete models for the particles of both substances using play-dough (that were put into transparent boxes). During the presentation of their model, they showed (and moved) their concrete representations keeping sheets of paper at the back of the transparent boxes, i.e. they used the representation of both macro and sub-micro elements of the system. The value of translation between the macro and sub-micro levels was shown by these students who, during their presentation, emphasised the role of the temperature changes in the process, the relationship between the temperature of the system and the movement of the molecules, and how specific details of their concrete models were essential in producing and expressing all their written ideas:

> The initial idea was to show that in the hot system the movement of the molecules is more intense than in the cold one. We intend to show that when we shake the molecules from the cold system they would separate: one molecule of N_2O_4 would form two of NO_2. Because of this, we fix the balls representing the nitrogen and the oxygen atoms with sticks – which made the N–O bond stronger in the NO_2 model – and we fix two NO_2 molecules to each other only using play-dough – which would result in a weak N–N bond (thus producing the model for the N_2O_4). We expected that when the system was shaken, the weak bond (between N–N) would easily break whilst the stronger ones (between N–O) would continue existing. Then we would be showing that one molecule of N_2O_4 would form two of NO_2. This explains why the colour of the system is changed.

Students in this group always worked simultaneously with the macro, sub-micro and symbolic levels. They did so trying to make the representation in one level be a support for the development of both a representation in another level and a plausible model that could explain the systems they observed. In Activity 3, when building

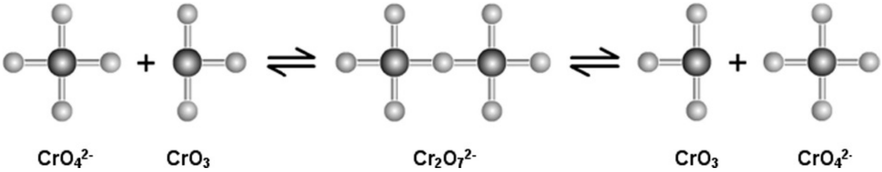

Fig. 12.3 Simulation produced by students to the 'resonance' model for the CrO_4^{2-} / $Cr_2O_7^{2-}$ system

their concrete representation for the CrO_4^{2-} / $Cr_2O_7^{2-}$ system, the students realised the importance of focusing on both the dynamic aspect of chemical reactions and the formulae of each ion. Thus, they proposed an original model for the equilibrium that was interpreted as a kind of resonance between those ions and a species that they created (CrO_3). When presenting their model to the class, they made the concrete models produce the 'resonance' (as shown in Fig. 12.3) and explained that

> Hydrogen ions (H^+) get one oxygen atom from the dichromate ion (CrO_4^{2-}) producing water and the species CrO_3. As the CrO_3 needs to become stable, it joins a chromate and produces a dichromate ($Cr_2O_7^{2-}$). The system would still contain chromate due to this 'movement' of the oxygen atom between two chrome atoms. In the dichromate, the chromate will share an oxygen atom with another chromate that is missing an oxygen atom. So, sometimes the oxygen atom will be forming a chromate, sometimes it will be forming a dichromate. Either one or the other!

This resonance model was a completely different idea that was understood by the class and the teacher only because they enacted a simulation with concrete models. This simulation explained some other details that could not readily be represented (such as the need for stability of the species) for they were always trying to establish relationships with the actual system that they had observed.

(vii) *Predictions were produced from the simultaneous production of explanations at macro and sub-micro levels*: When the students mentioned above shook the boxes containing their models (something that was done only when they presented their model to the whole class) and provided the above explanation, they observed that each of their models for the N_2O_4 molecules could really be split into the models of two NO_2 molecules. In so doing, they realised that the breaking of the bonds did not occur at the same time. Thus, they asserted that the dynamic feature of their model made them think that

> The reaction should occur as time goes by. That is why the change in the system colour was not an instantaneous one.

(viii) *When fluent in understanding, students could rely only on the symbolic level*: In the last activity, when students were asked to produce a model to explain what happened when the equilibrium between CrO_4^{2-} and $Cr_2O_7^{2-}$ was modified, most of them did not construct concrete models. When the teacher asked why they had preferred to only draw their models and to use the symbolic level, they answered:

> Now we can visualize the dynamic system from the drawings. So, we are able to perfectly explain our ideas from the drawings and by using the formulae.

(viii) *When fluent in understanding, students could move freely between the three levels of representation*: In the final questionnaire, students were challenged to explain a new model for chemical equilibrium in general. They were presented with a graphical representation for an equilibrium (the HI / H_2, I_2 system) and had to interpret it in order to answer some questions. In their answers, they were able to interpret the graphical information into both the macro and the sub-micro level. For instance, all the students expressed a clear and correct understanding that the equilibrium is reached when the concentration of all the species are constant (as a result of the occurrence of both reactions with the same velocity). This constant state explained the fact that, when a system is in equilibrium, it is not possible to observe a visible change. Moreover, they emphasised that the colour of the system would show us the coexistence of the particles of all species. For instance, the question involved the equilibrium between a violet gas (I_2) and two other colourless gases (H_2 and HI). A typical comment of the students was

> It (the system) is not completely colourless because there will always be I_2 particles in the system and it is a violet gas.

The students were also able to explain some of that information by using the symbolic level of representation (the equation that was presented together with the graph). This was observed when they made references to the line on the graph, making clear how they were interpreting it in order to reach their conclusions.

Conclusions and Implications

The teaching strategy adopted here led to students acquiring a good level of understanding of 'chemical equilibrium', as shown by the absence of common misconceptions in the assessment administered in Activity 6. The sequence of lessons showed that a progressive focus on each of the elements of 'Model of Modelling' and on aspects of the notion of 'chemical equilibrium' led to that success. This success has qualitatively validated the 'Model of Modelling' as the basis for teaching multi-faceted chemical models.

The role of the teacher has been shown to be vital. As students had to express their models for the sub-micro level in a concrete mode of representation, the teacher could identify aspects of their concrete representation (related to the codes of representation or to the ideas they wished to represent) that students did not express verbally. She questioned them, checking what they had really thought at different levels. The concrete expression of the models also allowed students to think about some questions that were not necessarily part of their initial mental models (e.g. the structure of the molecules, the direction of the collisions) – as their attempts to answer the teachers' questions made evident.

From the point of view of the focus of this book, the most important outcome was the demonstration that the use of the 'Model of Modelling' as a basis for producing and conducting teaching activities enabled the students to demonstrate their capability within and between the three levels of representation. Taking each of the five aspects of metavisual capability, given earlier, in turn:

1. *Understanding of the 'conventions of representation'*: From the outset, the students did not assume that their external representations were copies of the observed phenomenon. They progressively employed a range of components in their production of representations at the three levels. Moreover, they were always able to explain the codes of representation they decided to use, and to recognise the scope and limitations of their representations. Progress was made in respect of this aspect; further progress could be expected in situations where the use of a broader range of modes and sub-modes was called for.
2. *The capacity to 'translate' between the levels*: The role of the symbolic level in the production of explanations changed as the sequence of activities was followed, becoming suitably dominant in the later lessons. At the same time, mental 'switching' between the macro and sub-micro levels became ever more fluent. Moreover, during the process, students progressively increase their capacity to decide which level would be more adequate in a given situation.
3. *The capacity to construct a representation for a given purpose*: This was shown. Concrete (material) models were initially used, becoming progressively more sophisticated as the sequence of classes went on. Visual representations (diagrams) were readily employed. Most interestingly, symbolic representations were introduced and coherently used by the students despite the fact that they had not been systematically introduced to the conventions involved.
4. *The use of visualisation to make predictions*: This was done and the predictions tested both empirically and from thought experiments, sometimes with the help of the concrete models previously produced.
5. *The capacity to solve problems by analogy*: In the final questionnaire, the students showed themselves able to apply their understanding of chemical equilibrium to a novel context.

The practical work – the acquisition of empirical data – proved central to the demonstration of these capabilities. In respect of each desirable aspect of practical work, given earlier:

- The choice of specific systems where readily perceived changes of properties were associated with changes in the controlling chemical equilibrium enabled explanation in general and prediction in particular to be linked to behavioural changes.
- The students were able to produce progressively more sophisticated explanations as they experienced ever-more complex systems.

- The choice of systems studied was made so as to allow the ready perception of changes in properties.
- Representing the macro systems being studied evidently gave them a considerable start in producing representations of what was going on at the sub-micro level.
- The role of questions concerning the macro systems generated by the teacher, by individual students, and by groups of students, was a vital part of the processes of producing explanations and successful predictions.

Our conclusion is that a teaching sequence based on the 'Model of Modelling' is a valuable basis on which to lead students to a sound understanding of the complex ideas of chemistry and to the demonstration of metavisual capability. A series of conditions are necessary for success. First, opportunity to pose and respond to questions is central. Second, questions posed to and by students at different stages of the process should challenge them and support their creative thinking. Third, practical work that has a clear function in the learning process is vital. Fourth, the systems studied must show perceptible behavioural changes. Fifth, a sequence of carefully chosen systems is necessary.

This study suggests that much more research is needed into aspects of metacognitive capability and into the use of the 'Model of Modelling' if we are to provide fuller explanations of the processes involved in 'understanding the three levels of representation in chemistry'. For example:

- What are the 'codes of interpretation' of the modes and sub-modes of representation most commonly used in chemistry? These have never been codified.
- Are there differences between such 'codes of representation' used in chemistry and those used by chemistry teachers and textbook authors in producing teaching models? This seems to be a relevant factor influencing the success of teaching models in helping students to understand chemistry curricular models.
- How the understanding of the 'codes of representation' influence and are influenced by students' ability to use virtual models in informal educational contexts (e.g., museums, the internet)? Assuming both the role of virtual models today and the attraction they have for students, a comprehensive understanding of their codes of representation may contribute to increase students' motivation in learning science.
- How do individual students perceive the process of mentally moving between levels of representation and between modes of representation? Whilst tests of capability to operate within specific modes exist, there is little understanding of the processes involved in 'mentally moving' between them.
- What is the relationship between the way students use the three levels of representation and their capability to test their models? As testing models (from thought experiments and/or empirical ways) is an essential stage of the modelling process, their expertise in dealing with the three levels of representation seems to be vital for their learning in modelling-based contexts.

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