Models and Modeling in Science Education

Volume 3

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Visualization: Theory and Practice in Science Education

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Introduction

John K. Gilbert, Miriam Reiner and Mary Nakhleh

Interest in the educational value of material objects, pictures, diagrams, tables, graphs and the like, in science education has increased greatly in recent years (Gilbert, 2005). This has been facilitated to a large extent by the exponential rise in the memory capacity of personal computers and to the associated investment made in software development, which have combined to enable major innovations in instructional techniques to take place. For any educational innovation to succeed – to be widely adopted and persistently practiced – three associated aspects of any pedagogic innovation have to be initially addressed. Practical, user-friendly, examples of the innovation must be developed, tried out in classrooms, and their use evaluated. The contribution of the innovation to the curriculum must be explored – an identification of where the innovation may be used either to improve existing educational practice or to provide new forms of instruction. Why an innovation is successful – why it makes a worthwhile contribution to learning – must be established. These three aspects are inter-related and should be mutually reinforcing. The biggest issue of all – the provision of widespread and effective opportunities for teacher ‘continuing professional development’ in respect of the innovation – must be addressed from the outset.

The problem in many such cases, and certainly the case here, is that each one of these aspects is taken as a focus for work by a different academic community. The development of practical examples of such innovations is undertaken by the science community, often primarily interested in their use within scientific research and perhaps secondarily in their use in the training of future scientists. The curricular contribution of these innovations and opportunities for continuing professional development receives the attention of the science education community. The nature of their contribution to learning is seen as the province of the cognitive science community. The success of this type of innovation is hindered because these communities are not in any systematic direct contact with each other. We believe that one of the strengths of this book is that it brings together a collection of papers that contain the theoretical perspectives, understandings, and frameworks of several of

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these communities. We hope that this book can serve as the beginnings of a bridge between these diverse communities.

However, a lack of communication means that the drawing together of the contributions to the field by authors from diverse academic backgrounds will be hindered by their use of different specialist terminologies. Key words may be used in different ways, yet a commonality of meaning must be established if insights are to synthesised and new perspectives opened up. There are two generic systems in use in this area of innovation. In Convention 1, a representation is the depiction of anything; an external representation is one that has been placed in the public realm, in either a material object, visual, verbal, or symbolic form; an internal representation is one that is constructed mentally by an individual; a visualization is the understanding of, the meaning attributed to, an internal representation. In Convention 2, a visualization is a representation that has been placed in the public realm in either material object, visual, verbal, or symbolic form; the mental representation produced by an individual from a visualization is an image. The difference between the two Conventions lies in the meaning of the word visualization: in Convention 1 it is a verb (to visualize something is to mentally act on it); in Convention 2 it is a noun (a visualization is something that is in the public realm). There are, inevitably, phrases that cut across the two conventions: ‘visual representation’, ‘visuo-spatial thinking’, ‘representational insights’.

We have brought together the chapters of this book to promote the formation of links between those concerned respectively with theory, curriculum place, and pedagogic practice. In writing for and editing for it, we have decided to adopt Convention 1, for we wish to place the emphasis on the nature of the mental actions undertaken by individuals in using representations. Some of the contributing authors have adopted Convention 2. In order to avoid confusing the reader, where the word visualization is used in the Convention 2 sense, we have entered it as ‘visualization’, leaving the use of the word without parenthesis to be the meaning in Convention 1.

The book is divided into three Sections, dealing respectively with the first three aspects of innovation in respect of external representation, internal representation, and visualization.

Reference

Chapter 1
Visualization: An Emergent Field of Practice and Enquiry in Science Education

John K. Gilbert

Abstract Modelling as an element in scientific methodology and models as the outcome of modelling are both important aspects of the conduct of science and hence of science education. The chapter is concerned with the challenges that students face in understanding the three ‘levels’ at which models can be represented – ‘macro’, ‘sub-micro’, ‘symbolic’ – and the relationships between them. A model can, at a given level, be expressed in ‘external representations’ – those versions physically available to others – and in ‘internal representations’ – those versions available mentally to an individual person. The making of meaning for any such representation is ‘visualization’. It is of such importance in science and hence in science education that the acquisition of fluency in visualization is highly desirable and may be called ‘metavisual capability’ or ‘metavisualization’. Criteria for the attainment of metavisualization are proposed. Two approaches to the ontological categorization of representations are put forward, one based on the purpose which the representation is intended to serve, the other based on the dimensionality – 1D, 2D, 3D – of the representation. For the latter scheme, the requirements for metavisualization are discussed in some detail in terms of its components. General approaches to the development of metavisualization are outlined. Multi-disciplinary teams are needed if the research and development needed to improve visualization in science education is to take place.

Representation and Visualization in Science

In a nightmare world, we would perceive the world around us as being continuous and without structure. However, our survival as a species has been possible because we have evolved the ability to ‘cut up’ that world mentally into chunks about which we can think and hence give meaning to. This process of chunking, a part of all cognition, is modelling and the products of the mental actions that have taken place are models. Science, being concerned with the provision of explanations about the natural world, places an especial reliance on the generation and testing of models.
The models produced by science are expressed in three distinct representational levels (Johnstone, 1993) (Gabel, 1999). These are:

- **The macroscopic level.** This consists of what is seen in that which is studied. Simple examples in the formal science curriculum are: a solution of a pure chemical, a puck moving on an air-track, a cross-section of a leaf. These are all a representation in which some aspects of a natural phenomenon have been abstracted or detached from the whole for the purposes of study. Thus: a pure chemical was historically separated from the complex mixture in which it naturally occurs; a puck is an object that has been very largely liberated from the constraints of friction; a leaf is taken from a plant considered typical of a given family of plants. The macroscopic level is therefore a representation of a chunk of the world-as-experience that science is able to explore conveniently.

- **The sub-microscopic level.** This consists of representations of those entities that are inferred to underlie the macroscopic level, giving rise to the properties that it displays. Thus: molecules and ions are used to explain the properties of pure solutions; lubricants are used to explain the ready movement of an object; cells are used to explain the structure of a leaf.

- **The symbolic level.** This consists of any qualitative abstractions used to represent each item at the sub-microscopic level. These abstractions are used as ‘shorthand’ for the entities at the sub-microscopic level and are used to show quantitatively how many of each type of item are present at that level. Thus: chemical equations and the mathematical equations associated with the ‘mole’ concept are used jointly to represent a pure solution; mathematical equations are used alone to represent friction-free movement; while cells can be represented formally to indicate their type, position and number.

Being able to work within each of these levels and to mentally switch between them is a vital skill needed for the full appreciation of the explanations that science provides of natural phenomena. As we shall see, acquiring this skill presents challenges to many students. These types of work involve **visualization**, the making of meaning of representations. Visualization in concerned with **External Representation**, the systematic and focused public display of information in the form of pictures, diagrams, tables, and the like (Tufte, 1983). It is also concerned with **Internal Representation**, the mental production, storage and use of an image that often (but not always – see Chapter 4 on haptics) is the result of external representation. External and internal representations are linked in that their perception uses similar mental processes (Reisberg, 1997).

Visualization is thus, in the first instance, concerned with the formation of an internal representation from an external representation such that the nature and temporal/spatial relationships between the entities of which it is composed are retained. The attainment of visualization in a particular case can be shown by the production, the expression, of a version of the original for a particular purpose. An internal representation must be capable of mental use in the making of predictions about the behaviour of a phenomenon under specific conditions. 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: this is creativity.

Visualization is of especial importance in three aspects of the learning of science.

- Learning specific consensus or historical models
  A model that is currently used by a community of scientists in cutting-edge enquiry can be called a consensus model. Contemporary examples are: the double-helix model of DNA, the P-N junction model of a transistor, the gene in biology. A model that once had consensus status but which, although superseded in cutting-edge research, still has explanatory value, is known as an historical model (Gilbert, Boulter, & Rutherford, 2000). Historical and consensus models, or those simplified versions that can be called curriculum models, are invaluable in science education. First, being the major products of science, ‘learning science’ must involve learning the nature and use of these. Second, because a particular model can be used to provide an acceptable explanation of a wide range of phenomena and specific facts, it is a useful way of reducing, by chunking, the ever-growing factual load of the science curriculum. Visualizing external representations of such models and being able to form internal representations of them are at the core of turning them into knowledge.

- Learning to develop new qualitative models
  A major task in the conduct of a scientific enquiry into a hitherto-unexplored phenomenon is the production of a model of it: the process of modelling. Given its importance, all students of science should learn the complex skills of modelling. It has been suggested that these skills can be developed by following the sequence of learning how: to use an established model; to revise an established model; to reconstruct an established model; to construct a model de novo (Justi & Gilbert, 2002). External and internal representation, together with the associated visualization, is needed at each of these stages.

- Learning to develop new quantitative models
  Once science has developed a useable qualitative model of a phenomenon, a quantitative version of it must be produced for a comprehensive representation to be available. Progress in the scientific enquiry into a field is indicated by the value of a particular combination of qualitative and quantitative models in making successful predictions about its properties. Again, visualization is central the production of representations of these models.

**Metavisualization and Criteria for its Attainment**

Representation – both external and internal – is ubiquitously employed across all aspects of life: the physical, social, and intellectual environment. The associated visualization can be called ‘spatial thinking’ (N.R.C., 2006) (p. 28). A fluent performance in visualization has been described as requiring metavisualization and involving the ability to acquire, monitor, integrate, and extend, learning from
representations (Gilbert, 2005) (p. 15). Before criteria for the attainment of metavi-
sualization can be put forward, the ontology of its subject matter, the representa-
tions, must be put discussed. Typologies can be based either on the purpose for
which a representation is created or on the dimensionality of the product

**The Purpose for which a Model is Produced**

All models are produced by the use of analogy (Hesse, 1966): the *target* which is
the subject of the model is depicted by a partial comparison with a *source*. The
classification scheme of Harré (Harre, 1970) (pp. 34–61) is binary: either the target
and the source are the same thing (they are *homomorphs*) or they are not (they are
*paramorphs*). Homographs may be either *micro-* and *macro-morphs*, being respec-
tively either smaller (e.g. of an aeroplane) or bigger (e.g. of a virus) than the target.
They can also be *teleiomorphs*, being either idealisations of the target where, whilst
all the characteristics of it are present, some of them are emphasised (e.g. a so-called
‘fashion model’) or an abstraction based on the target, where only some of the prop-
erties are represented (e.g. the use of coloured wire to represent the vascular system
of animals). *Metromorphs* are based on a target which is a class of phenomena rather
than an individual example of a phenomenon, average properties being represented
(e.g. of a ‘typical family’). The purpose in using a homomorph is to focus attention
upon, to emphasise, only some aspects of the target. Paramorphs, on the other hand,
are used to model processes rather than objects, the processes taking place being
thought to be the *same* in the target and the source (e.g. modelling a human per-
formance of an arithmetic calculation based on how a computer functions) or only
*analogous* to it (e.g. the electronic simulation of hydraulic networks). Although this
scheme will not be discussed further here, it does offer the possibility to relating the
sources of models and/ or the ways of representing them to the purposes to which
they are to be put.

**The Dimensionality of the Representation**

Because visualization depends on the perception and mental manipulation of objects
in space, a system is suggested which depends on the number of physical dimensions
of the representation. The idea that modelling involves the progressive reduction of
the experienced world to a set of abstract signs (Bowen & Roth, 2005) (p. 1064) can
be set out in terms of dimensions are follows:

(Three dimensions) *are simplified to* (Two dimensions) *are simplified to*
(One dimension)

This enables us to position the levels of external representation roughly in terms
of dimensions, as in Table 1.1:
Table 1.1  Types of representation for the triplets of dimensions and levels

<table>
<thead>
<tr>
<th>Macro level</th>
<th>Three dimensional (3D)</th>
<th>Two dimensional (2D)</th>
<th>One dimensional (1D)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Perception of the</td>
<td>Perception of the</td>
<td>Symbols and equations</td>
</tr>
<tr>
<td></td>
<td>world-as-experienced</td>
<td>world-as-experienced</td>
<td></td>
</tr>
<tr>
<td>Sub-micro level</td>
<td>Gestures, concrete</td>
<td>Photographs, virtual</td>
<td></td>
</tr>
<tr>
<td></td>
<td>representations</td>
<td>representations,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>diagrams, graphs,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>data arrays</td>
<td></td>
</tr>
<tr>
<td>Symbolic level</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

The first systematic encounter that students have with representations in 3D is through the laboratory practical work that is included in the science curricula of many countries. In the process of learning the scientific explanations at the sub-micro level for the phenomena encountered in that practical work, they often make gestures in 3D and use concrete (or material) representations e.g. the ‘skeletal’ ‘ball-and-stick’ and ‘space filling’ representations used in chemistry.

Students can initially encounter representations in 2D during their laboratory practical work e.g. a cross-section of a leaf or of a wave. However, the major sources of experience with 2D representations are through the use of photographs (whether directly of 3D phenomena or the products of scientific instrumentation e.g. spectrographs), virtual representations (those pseudo-3D representations produced on computer screens by the use of modeling software packages), diagrams of all types, graphs. Whilst photographs are often not considered as representations, this will be done here because they both frame the perception of the viewer and provide strong interpretational cues for their visualization. The genre of diagrams covers a wide range: data maps, time-series, space-time narratives, relational graphs (Tufte, 1983). Graphs include scatterplots, pie-charts, and Cartesian line graphs. The word ‘array’ is used to cover the range of forms of number display: tables and histograms.

1D representation is inherently an abstraction and consists of symbols. Some commonly encountered examples in science education are chemical symbols, chemical equations, and mathematical equations.

**Criteria for Metavisualization**

Three criteria are suggestion for the attainment of metavisual status. The person concerned must be able to:

1. demonstrate an understanding of the ‘convention of representation’ for all the modes and sub-modes of 3D, 2D, 1D representations. That is, what they can and cannot represent.
2. demonstrate a capacity to translate a given model between the modes and sub-modes in which it can be depicted.
3. demonstrate the capacity to be able to construct a representation within any mode and sub-mode of dimensionality for a given purpose.

4. demonstrate the ability to solve novel problems using a model-based approach. This can be done by the drawing of a suitable analogy to an already-solved problem (Polya, 1957) (p. 27), or either by providing a visual-recall cue and by removing irrelevant material from perception of the problem (Beveridge & Parkins, 1987) (p. 235).

**Acquiring Meta Status for the Visualization of External Representations at the Macro-level**

Many, if not most, science educators would not see the macro-level as being an ‘external representation’ that requires ‘visualization’. Rather, they would see it as being the world-as-experienced itself i.e. as ‘reality’. I would argue that this commonplace agreement is misguided. Whilst science certainly does seek to provide explanations of natural phenomena, the complexity of these requires that exemplars, whether relatively simple or artificially simplified versions of the world-as-experienced, are actually investigated. In short, science investigates idealised external representations of the everyday world.

In both science and science education, those external representations of the macro-level are the phenomena that are actually investigated in the laboratory, in field studies, or in simulations of both. As scientific enquiry into a particular field advances, the versions of the phenomena investigated become either ever closer to or ever more distant from the naturally occurring phenomena. However, science education rarely follows far down this path or, if does so, it does so slowly. It is vital that practical experience is included in science education, for there is ample evidence e.g. (Driver, Guesne, & Tiberghien, 1985) that students needs guidance as to what aspects of a phenomenon are to be the focus of a particular scientific study. Moreover, if transfer of learning from ‘scientific’ to ‘everyday’ contexts is sought, students must have structured experience of how to model macro-phenomena.

Such investigations are, in the formal science curriculum, collectively called ‘practical work’. A summary of research findings about practical work, heavily based on that produced by Judith Bennett (Bennett, 2003) (p. 76), is as follows:

- practical work by students forms a significant part of the science curriculum in many countries;
- students generally report practical work to be enjoyable;
- practical work serves a wide variety of purposes;
- there is a lack of clarity over the purposes of much practical work;
- different types of practical work are needed to achieve different purposes;
- practical work makes phenomena real for students;
- practical work can help students gain some understanding of how science progresses;
because of the ambiguity over purposes, practical work can sometimes hinder
the development of an understanding of scientific ideas;
the development of transferable skills through practical work is doubtful;
students’ performance in practical work depends on their understanding of the
scientific ideas underlying it;
some aspects of practical work are problematic for students, particularly the con-

trol of variables and judgment about data reliability;
teachers’ assessment has an important role in the valid assessment of achieve-
ment in practical work.
The main purposes of practical work have been summarised by (Hodson, 1990) as:

- to teach laboratory skills;
- to enhance the learning of scientific knowledge;
- to provide insight into the nature of scientific methodology;
- to develop ‘scientific attitudes’ e.g. objectivity;
- to motivate students to learn by providing them with enjoyment and stimulating
their interest.

The review of research suggests that the educational impact of particular examples
of practical work is diminished because of an ambiguity of address to these purposes
(Nakhleh, Polles, & Malina, 2002). Developing the capacity to ‘visualize an external
representation at the macro level’ need not be hindered by this ambiguity, but would
certainly be enhanced if explicit attention was paid to this requirement within the
above purposes as follows:

- showing how the version of a phenomenon was related to, produced or derived
  from, a naturally occurring phenomenon;
- focusing on those aspects of a phenomenon under study that require explanation
to be provided through sub-microscopic and symbolic levels of representation;
- 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 rela-
tionship 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.

**Acquiring Meta Status for the Visualization of External 3D Representations at the Sub-micro Level**

**Gestures**

Arguably a very prevalent, yet almost completely un-researched, form of 3D repre-
sentation used in science and science education is the ‘gesture’: moving the hands
and arms during a discussion. (Roth & Welzel, 2001), on the basis of science classroom-based studies, concluded that:

1. gestures arise from the experiences in the phenomenal world, most frequently express scientific content before students master discourse, and allow students to construct complex explanations by lowering the cognitive load; 2. gestures provide a medium on which the development of scientific discourse can piggyback, and 3. gestures provide the material that ‘glues’ layers of perceptually accessible entities and abstract concepts (p. 103)

Whilst the acquisition of a formal technical vocabulary did lead to a decline in dependence on gesture, Roth and Welzel found that its use was retained. They confirmed the view that gestures can take one of three forms, as being: iconic, where their surface structure is isomorphic with their content; deistic, where they emphasis salient aspects of the phenomenon under discussion; metaphoric, for example where a sweeping gesture indicates the notion of ‘limit’. We suggest that the teaching of, or at least the encouraging of, the use of gesture in science classes – particularly when explanations are being constructed – could support the development of 3D metavisual capability. It may well be that students from different cultures bring varying usages of gesture to the study of science.

**Structural Representations**

However, when 3D external representation is discussed, it is usually the range of structural representations that is being referred to. In the case of chemistry, they can be divided into three types: ‘open’ (ball-and-stick, skeletal), ‘space filling’ (molecular, ionic) and ‘orbital’ (Ingham & Gilbert, 1991) (p. 194). These are, in Harré’s terms, paramorphs, that are used to represent severally the dimensions of nature, size, and arrangement. (Hesse, 1966) divided the aspects of any source into two major parts: the ‘positive’ analogy, those aspects that have some similarity to aspects of the target; the ‘negative’ analogy, those aspects that definitely do not have any similarity to aspects of the target. The positive analogies to different aspects of a target that are represented in the various types of 3D external visualizations are given in Table 1.2.

There is long-standing evidence that students get confused between the several representational systems usually available for a phenomenon, leading to inadequate

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**Table 1.2** Similarities represented in different 3D representational systems (+ indicates ‘present’ and – indicates absence)

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Open B &amp; S</th>
<th>Skeletal</th>
<th>Space Filling Molecular</th>
<th>Space Filling Ionic</th>
<th>Orbital</th>
</tr>
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<tr>
<td>Entity natures</td>
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</table>
or incorrect visualization. For example, (Carr & Oxenham, 1985) found that high school students often confused the precepts of the Lowry-Bronsted and Arrhenius models of acids and bases. Even when they had been taught more advanced models, (Coll & Treagust, 2001) found that university chemistry students tended to prefer to use the simpler (often more historically distant) models that they had learnt at school. One problem seems to be that students are not systematically taught the conventions circumscribing particular types of representation. For example, (Ingham & Gilbert, 1991) found that, in respect of the use of ball-and-stick representations, of a sample of 39 undergraduate and graduate chemists, 6 did not recall ever being taught the conventions, 24 claimed to be unfamiliar with the conventions involved (yet were able to deduce them in an interview situation), and 9 were both unfamiliar with them and were unable to deduce them.

Notwithstanding these problems, the use of 3D external representations in teaching has been found beneficial. For example, (Huddle, White, & Rogers, 2000) found that ‘teaching models’ (Gilbert & Boulter, 2000) were effective in correcting the misconceptions of high school and university students in the subject of electrochemistry. There is no doubt that students are increasingly willing to use multiple types of 3D representation to explain a phenomenon as they gain experience of them, as (Harrison & Treagust, 2001) found in a longitudinal study of high school chemistry them, as (Harrison & Treagust, 2001) found in a longitudinal particular models, providing them with opportunities to explore the scope and limitations of those models, and encouraging them to use several models in a given field, both improves the understanding of the field generally and enables the students to appreciate the value of the particular models used more clearly (Harrison & Treagust, 2000).

**Acquiring Meta Status for the Visualization of External 2D Representations at the Sub-micro Level**

The complex material here can best be presented with the use of a ‘spectrum’ of types of representations which ranges from the near – 3D to the near –1D.

**Virtual Representation**

Virtual, or pseudo-3D, representations are produced using software packages on a computer. Although in fact 2D, they are encoded by the user as 3D by virtue of the inclusion of a full range of ‘visual cues’ (e.g. shading, distancing). Their value is enhanced by the ability of the computer system to ‘rotate’ and ‘invert’ them i.e. they are dynamic in nature. This book is a testimony to the growing influence of virtual approaches to representation in science education, with efforts at research gradually rising to meet the extent of work on system development. In a careful study of representations in general, Verk Savec found that students’ ability to perceive a 3D molecular structure as such decreased when this was done with the aide of 3D
representations, through the use of static virtual representations, to the use of static 2D representations (Ferk Savec, Vrtacnik, & Gilbert, 2005) (p. 269). The value of dynamic representations, which make full use of the medium, has been summarised by (Lowe, 2004):

(As) a good match between the representational medium and the characteristics of the phenomenon being represented is considered instructionally desirable—animations have the advantage of being able to present situational dynamics explicitly and appropriately so that the majority of learners’ processing capability could be devoted to comprehending the content directly—Interactive animations that can be freely interrogated by learners may help to reduce the likelihood of information processing problems (p. 258/9)

The attainment of metavisual capability must, in today’s world, involve students being able to fluently scan the internal structure of a dynamic representation. Lowe (2004) (p. 262) has set out the strategies involved in the successful scanning of such visualizations: there is some evidence that they can be developed in students (Ploetzner & Lowe, 2004). Mentoring by an expert during problem solving would seem an obvious strategy, albeit a very expensive one.

Photographs

Photographs are often not discussed alongside other forms of representation, being perhaps sub-consciously considered more ‘real’ than other forms. Yet, the similarity to the-world-as-experienced is delusory, for photographs frame the field of perception of the viewer and, by virtue of the notion of ‘composition’, provide strong interpretative cues to the viewer as to its visualization.

In one of the very few studies of the use of photographs in science education, (Pozzer & Roth, 2003) examined their use in high school biology textbooks. Their work suggests some items of ‘good practice’ which would enable students to understanding fully (i.e. to visualize) the message of a photograph when inserted in a text i.e.

- the background to the phenomenon which is the focus of the photograph should be both distinct and relevant;
- multiple photographs, taking different perspectives on, or at different magnification of, the focal phenomenon, should be used;
- the photograph should have a caption which links it appropriately to the main text;
- the text should make distinctive use of a photograph that is explicitly referred to;
- learning from the photograph should be encouraged by the insertion of suitable questions into the text.

The extent to which these precepts were followed in the four Brazilian high school biology textbooks analysed (Pozzer & Roth, p. 1094) is given in summary form in Table 1.3:

Different educational systems do, of course, rely on the use of textbooks to varying degrees. Biology as a subject lends itself to the use of decorative and illustrative photographs. However, the Pozzer and Roth study does show that promoting
metavisualization calls for a systematic development of the genre of photographs, with much more emphasis being placed on the ‘explanatory’ and ‘complementary’ forms of use.

**Diagrams**

Although diagrams are widely used in textbooks, there seem to be no agreed conventions on their design and the implications of these for learning. In an interesting small-scale study, (Newberry, 2002) got a class of high-achieving 14–15 year olds (U.K., Year 10) to comment on the value for learning of the diagrams that they had encountered in their recently-completed study of the ‘Rock Cycle’. The pupils collectively produced the following hierarchy:

- Cartoons were viewed as fun and memorable but more suitable for younger pupils. Even then the pupils expressed reservations, feeling that cartoons may lead to misconceptions and are limited tools for explaining complicated phenomena;
- Pictorial diagrams were believed to be the best kind for pupils like themselves to grasp ideas in the first place;
- Thereafter, diagrams with increasing amounts of labelling and process arrows would be of steadily increasing value;
- Abstract line drawing diagrams were perceived to be the most suitable for higher achieving pupils and for others as a revision aid (for public examinations) once the basic ideas had been understood (p. 7)

Whilst the ‘pictorial diagrams’ and the ‘abstract line drawing diagrams’ may be seen as canonical forms, each with a finite set of ‘codes of interpretation’ relating the diagram to the phenomenon shown, there are myriad intermediate forms. The codes of interpretation for even the canonical forms, such as those found by Newberry’s pupils for the ‘Rock Cycle’, have not yet been elucidated, although extensive discursive work on ‘the grammar of visual design’ has taken place (Kress & Van Leeuwen, 1996).

In an attempt to promote ‘visual literacy’, what is called ‘metavisual capability’, attention has been paid to the inter-relation between the interpretation of diagrams

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**Table 1.3** The different approaches to the use of photographs in Brazilian biology textbooks

<table>
<thead>
<tr>
<th>Category of photograph</th>
<th>Description</th>
<th>Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decorative</td>
<td>Photographs without captions or references in the text</td>
<td>5.4</td>
</tr>
<tr>
<td>Illustrative</td>
<td>Photograph with the name of the phenomenon only in the caption</td>
<td>35.1</td>
</tr>
<tr>
<td>Explanatory</td>
<td>Photograph with the name and some explanation of the phenomenon in the caption</td>
<td>28.4</td>
</tr>
<tr>
<td>Complementary</td>
<td>Photograph with the name of the phenomenon and some additional information not given in the text</td>
<td>31.1</td>
</tr>
</tbody>
</table>
and of the text in which they are placed. This inter-relation between the material reality of the diagram and social reality in which it is embedded and interpreted is seen to produce a semiotic reality (Unsworth, 2001) (p. 72). Put succinctly:

- representational/ideational structures verbally and visually {jointly} construct the nature of events, the objects and participants involved, and the circumstances in which they occur;
- interactive/interpersonal verbal and visual resources {jointly} construct the nature of relationships amongst speakers/listeners, writers/readers, and viewers and what is viewed;
- compositional/textual meanings are concerned with the distribution of the information value or relative emphasis amongst elements of the text and image

(Unsworth, 2001) (p. 72)

If a student is to achieve metavisual capability in respect of diagrams, two primary conditions have to be met. First, the codes of interpretation of the material content of diagrams and for the social contexts embedded within them must be known. Second, the way that diagrams relate to the structure of the text must be known. Given the current lack of attention to these issues at a pragmatic level directly accessible to students, the attainment of metavisual capability is perhaps more a matter of luck than instructional judgment.

**Graphs**

The importance of representation in the form of graphs is emphasized by its centrality in any list of ways of handling data, for example that expressed by the National Research Council. Thus, students should be able to:

- describe and represent relationships with tables, graphs, and rules;
- analyse functional relationships to explain how a change in one quantity results in a change in another;
- systematically collect, organize, and describe data;
- estimate, make and use measurements to describe and compare phenomena;
- construct, read, and interpret, tables, charts, and graphs,
- make inferences and convincing arguments that are based on data analysis;
- evaluate arguments that are based on data analysis;
- represent situations and number patterns with tables, graphs, verbal rules, and equations and explore the inter-relationships of these representations;
- analyse tables and graphs to identify properties and relationships

(NRC, 1996) (pp. 105–121)

This emphasis is because:

Graphing methods tend to show data sets as a whole, allowing us to summarize the general behavior and to study detail. This leads to much more thorough data analysis (Cleveland, 1985) (p. 10).

Again, the sub-forms of ‘graph’ are multiple. However, (Tufte, 1983) has identified four canonical forms:
• data maps. Here the positions of objects or events are represented in an identifiable geographical space. For example, the distribution of a wild flower in a meadow
• Time series. Here the positions of objects or events are represented as a function of time. For example, the migration of a species of bird over the years;
• Space-time narratives. Here the positions of objects or events are represented as function of both time and identifiable geographical space. For example, the migration of a species of bird over the years as a function of points on the migration route;
• Relational graphics. Here the variation of one abstract concept with another is represented.

Whilst science and science education make use of all four forms, arguably the greatest use is made of the fourth – ‘relational graphics’.

The problems that students have with attributing meaning to – visualizing – the various sub-forms of relational (or Cartesian) graphs must start within their degree of experience of them. (Roth, Bowen, & McGinn, 1999) identified four sub-forms that were used in ecology journals: scatter plots including data points only; scatter plots with a line connecting points; scatter plots with best-fit curves; graphs of a mathematical model. When they looked at high school ecology textbooks, they found that these four were hardly ever present, the dominant sub-form being a quasi-qualitative graphical model without scales or units. It is hardly surprising then that there is a difference between the quality of ‘expert’ and ‘novice’ interpretation of the ‘scientific’ sub-forms. (Bowen, Roth, & McGinn, 1999) found that: ‘experts’ established meaning for a graph by drawing on a range of interpretative frameworks, whilst ‘novices’ had a limited range of such resources; that ‘experts’ had a broader range of linguistic resources to draw on that did the ‘novices’. The situation was made more complex by the fact that scientists from different specialisms tend to use different interpretational frameworks for the same task. An inferred absence of ‘graphical education’ inevitably leads to general problems in graph use, for example an inability to transfer learning about graphs from the school subject of ‘mathematics’ to that of ‘science’. Thus (Aberg-Bengtsson, 1999) noted that upper secondary students were unable to locate specific information in a graph and lacked a perception of the overall trends contained within a graph. These types of problem, that have been widely observed, perhaps partially stem from their science teachers: (Bowen & Roth, 2005) found that pre-service science teachers preferred to use only scatter plots and ‘best fit lines’ to represent data.

If we wish all students to achieve metavisual capability in respect of graphs, then they must experience all the sub-forms, also being provided with a commentary on the scope and limitations of each. Most importantly, the graphs that they encounter must be of excellent quality, in that they:

• show the data;
• induce the viewer to think about the substance (or what is being represented);
• avoid distorting what the data have to say;
• present many numbers in a small space;
• make large data sets coherent;
Acquiring Meta Status for the Visualization of External Representations at the Symbolic Level

A major group of external symbolic representations that is unique to science is composed of ‘chemical equations’. It is common, at least in the UK, to introduce students to the idea of chemical equations by means of ‘word equations’, in which only the names of the species are given. For example:

\[
\text{Zinc} + \text{hydrochloric acid} \rightarrow \text{zinc chloride} + \text{water}
\]

This strategy has several attractions to teachers. First, it links representation at the symbolic level directly to that at the macro level, without the complexity of the sub-micro level being interposed. Second, it enables teachers to group reactions e.g. metal + acid, acid + salt, metal oxide + acid etc. At a more sophisticated level, reactions can be grouped into types along somewhat more theoretical lines e.g. displacement, neutralization, redox, thermal decomposition. However, as (Taber, 2002) (pp.141–4) points out, such an approach has a number of drawbacks. First, word equations are not based on the law of conservation of matter i.e. that the same amounts of all elements (in whatever form) must appear on both sides of the equation. Second, students are often unfamiliar with the large number of technical terms used e.g. ‘tetraoxosulphate (VI)’ (for the more commonly used ‘sulphate’). These problems lead to students being unable to perceive the changes occurring as a whole. For these reasons, word equations are often seen as an inadequate bridge to formulae equations.

There are many sub-forms of formulae equations (Peters, 2006). The simplest sub-form merely states the names of species in terms the elements involved e.g.

\[
\text{HCl} + \text{NaOH} \rightarrow \text{NaCl} + \text{H}_2\text{O}
\]

The problem with this example of the first sub-type is that the reaction will not proceed under the anhydrous conditions implied. A more informative version includes the state symbols e.g.

\[
\text{HCl}_{(aq)} + \text{NaOH}_{(aq)} \rightarrow \text{NaCl}_{(aq)} + \text{H}_2\text{O}_{(l)}
\]

Several sub-forms introduce simplicity into the equation by removing unnecessary data, thus concentrating attention of the essence of the changes taking place and hence enhancing visualization. In one sub-form, ‘spectator’ sub-species are removed e.g.
Where a reaction is complex, it is usual to provide a ‘shorthand’ version of the formulae equation by placing statements about such matters as the energy change occurring, the presence of a catalyst, the nature of any extraordinary physical conditions, above the arrow linking the reactants and products. For example, for the oxidation of ethanol to ethanoic acid

\[
\text{Cr}_2\text{O}_7^{2-}/\text{H}^+_{(aq)} \\
\text{C}_2\text{H}_5\text{OH}_{(l)} \rightarrow \text{CH}_3\text{COOH}_{(aq)}
\]

In theory at least, all chemical reactions are reversible. However, where the equilibrium constant is very high, or where the physical conditions drive the equilibrium towards the products side of the equation, it is usual to use a unidirectional rather than a reversible arrow between the reactants and products.

Achieving metavisualization in respect of chemical equations must involve the student in becoming aware of the scope and limitations of each sub-form in use. This level of detail will be needed for not only do textbooks use a range of these sub-forms but, even more disturbing, their own conventions that are a mixture of the generic forms e.g

\[
\text{Zn} + 2\text{H}^+_{(aq)} \rightarrow \text{Zn}^{2+} + \text{H}_2
\]

### Visualization and the Translation Between Representations at the 3D, 2D, 1D, Levels

The ability to ascribe meaning to (i.e. to visualize) a representation that is 3D, 2D, or 1D, is the key aspect of metavisualization. A more advanced skill is that of using a visualization at one level of representation as the basis of a visualization of the same model at a different level of representation. The use of the metaphor ‘the translation of representations’ gives a flavour of the value and hazards of this enterprise.

Inevitably, given the lack of a general ‘visual education’, it is not surprising that students find the multiple possibilities (as many as: 1D to 2D, 1D to 3D, 2D to 1D, 3D to 1D, 2D to 3D, 3D to 2D) that link the macro to the sub-micro to the symbolic levels difficult to master. For example, (Hinton & Nakhleh, 1999) found that undergraduate chemistry students were able to form representations of a chemical phenomenon at the macro and symbolic levels, yet found it difficult to link these to the equivalent representations at the sub-micro level.

Expert chemists must be able to do this (Kosma, 2003; Kosma, Chin, Russell, & Marx, 2000; Kosma & Russell, 1997), a requirement that must have its equivalence in the other sciences, because there is evidence that doing so enhances capability to solve problems, whether explicitly requiring visualization or not (Bodner & McMillen, 1986).
Acquiring Meta Status for the Visualization of Internal Representations

Internal representation, being most commonly the outcome of the perception of an external representation, inevitably involves memory. (Nelson & Narens, 1994) have produced a three stage model of memory, to which a fourth stage has been suggested (Gilbert, 2005), that can be applied to the acquisition and visualization of internal representations. As a learner becomes increasingly metavisually capable, that person:

- becomes increasingly able to control the acquisition of internal representations. Confidence in the ability to visualize existing internal representation increases as does the judgment of how difficult it will be to acquire and make meaning of new internal representations;
- becomes increasingly able to retain an internal representation and its associated visualization;
- becomes increasingly confident that an internal representation will be retrieved in an accurate form such that its visualization can be relied on;
- becomes increasingly able to consciously amend a retrieved internal representation for particular purposes. This capability leads to amended external representations being consciously produced.

Supporting the acquisition of metavisual capability in respect of internal representations is something of a mystery. It would seem to depend on providing students with amble opportunities to both develop internal representations and to express them as external representations.

Sex Differences in Visualization

Whether males and females have the capabilities in respect of visualization continues to be the source of much, sometimes frivolous, discussion. That the same abilities are present is not in doubt:

Infants begin with certain spatial skills—and these skills change with development (some of which include): the reweighting of initial spatial coding systems as the infant learns more about the world, the advent of place learning, and the acquisition of perspective taking and mental rotation. Children also begin to use symbolic representations of space, including maps, models and linguistic descriptions, and they learn to think about space and to use spatial representations for thinking (Newcombe & Learmonth, 2005) (p. 213)

But how far and how fast do these developments naturally take place? In a meta-analysis of the field, conducted 20 years ago, Linn and Petersen concluded that:

(a) sex differences arise in some types of spatial ability but not others (b) large sex differences are found on measures of spatial perception, and (c) when sex differences are found, they can be detected across the life span. (Linn & Petersen, 1985) (p. 1479)
In general terms, these differences favour males. It does seem that both sexes improve their spatial abilities when provided with specific training, but that the differences never entirely disappear (Halpern & Collaer, 2005) (p. 200).

**Developing the Skills of Metavisualization**

Acquiring metavisual status implies being able to progressively acquire understanding of (i.e. being able to visualize) representations at the 3D, 2D, 1D, level and being able to move between them. Whilst only concerned with representations in chemistry and not using the terminology adopted in this chapter, the scheme of ‘progression in representational competence’ by Kozma and Russell (see Table 1.4) (Kozma & Russell, 2005) is helpful as it suggests what educational opportunities should be provided. However, this progression does need to be recast in terms of the ‘levels of representation’ that are the focus of this chapter.

I would argue that two strategies have to underlie this development. First, a strategy is needed is to develop the epistemological beliefs about the nature of knowledge used by students. Perry identified four major positions in the epistemological development of undergraduate students (Perry, 1970). When displaying dualism, students see knowledge as either right or wrong. This gives way to multiplicity in which all knowledge has an equal claim to acceptance. Later comes relativism, in which the value of knowledge is relative and context bound. Finally, in commitment to relativism, knowledge is seen to be enmeshed in a framework of ethical and social responsibility whilst also being contextually appropriate. In the absence of much, if any, specific teaching about the nature of knowledge, one would imagine that school and university science students are still, 30+ years after Perry’s fascinating study, located at the bottom end of this typology. Second, the students must come to have an acceptable understanding of the concept of ‘model’ itself. (Grosslight, Unger, Jay, & Smith, 1991) developed a scheme to represent the development of this understanding. At Level 1, students believed that a model is a direct representation of reality. At Level 2, a model remains a direct representation of reality, but it is incomplete in that some aspects are neglected. Such a model is used for communication rather than the exploration of ideas. At Level 3, a model is a tool for thinking, being altered by the modeler to emphasise particular issues. Grosslight et al. found that, at the time of their study and in the absence of any specific education about the nature of models, most lower secondary school students displayed an understanding at Level 1, with only a few upper secondary students displaying a Level 2 understanding, the attainment of Level 3 being restricted to professional scientists. However, in the years following the Grosslight et al. study and with a gradually improving awareness of the importance of models and of epistemological commitments in science and science education, the situation has improved considerably, as a recent study shows (Chittleborough, Treagust, Mamiala, & Mocerino, 2005).

Four sets of tactics can be adopted to facilitate the developments of a more useful epistemological commitment and understanding of the ‘nature of model’:
Table 1.4 Summary of representational competence levels

**LEVEL 1: REPRESENTATION AS DEPICTION**

When asked to represent a physical phenomenon, the person generates representations of the phenomenon based only on its physical features. That is, the representation is an isomorphic, iconic depiction of the phenomenon at a point in time.

**LEVEL 2: EARLY SYMBOLIC SKILLS**

When asked to represent a physical phenomenon, the person generates representations of the phenomenon based on its physical features but also includes some symbolic elements to accommodate the limitations of the medium (e.g., use of symbolic elements such as arrows to represent dynamic notions, such as time or motion or an observable cause, in a static medium, such as paper). The person may be familiar with a formal representation system but its use is merely a literal reading of a representation’s surface features without regard to syntax and semantics.

**LEVEL 3: SYNTACTIC USE OF FORMAL REPRESENTATIONS**

When asked to represent a physical phenomenon, the person generates representations of the phenomenon based on both observed physical features and unobserved, underlying entities or processes (such as an unobserved cause), even though the representational system may be invented and idiosyncratic and the represented entities or processes may not be scientifically accurate. The person is able to correctly use formal representations but focuses on the syntax of use, rather than the meaning of the representation. Similarly, the person makes connections across two different representations of the same phenomenon based only on syntactic rules or shared surface features, rather than the shared, underlying meaning of the different representations and their features.

**LEVEL 4: SEMANTIC USE OF FORMAL REPRESENTATIONS**

When asked to represent a physical phenomenon, the person correctly uses a formal symbol system to represent underlying, non-observable entities and processes. The person is able to use a formal representation system based on both syntactic rules and meaning relative to some physical phenomenon that it represents. The person is able to make connections across two different representations or transform one representation to another based on the shared meaning of the different representations and their features. The person can provide a common underlying meaning for several kinds of superficially different representations and transform any given representation into an equivalent representation in another form. The person spontaneously uses representations to explain a phenomenon, solve a problem, or make a prediction.

**LEVEL 5: REFLECTIVE, RHETORICAL USE OF REPRESENTATIONS**

When asked to explain a physical phenomenon, the person uses one or more representations to explain the relationship between physical properties and underlying entities and processes. The person can use specific features of the representation to warrant claims within a social, rhetorical context. He or she can select or construct the representation most appropriate for a particular situation and explain why that representation is more appropriate than another. The person is able to take the epistemological position that we are not able to directly experience certain phenomena and these can be understood only through their representations. Consequently, this understanding is open to interpretation and confidence in an interpretation is increased to the extent that representations can be made to correspond to each other in important ways and these arguments are compelling to others within the community.

The explicit use of several models and levels of representation when teaching a given topic. Both (Harrison & Treagust, 1998) and (Chittleborough et al., 2005) provide evidence, both direct and indirect, that doing so is helpful.

The explicit teaching of ‘the principles of analogy’. This will help students to understand not only how particular models are developed but also how the ‘translation between levels of representation’ can take place. The ‘Focus, Action, Reflection’ (FAR) approach seems to be particularly effective (Treagust, Harrison, & Venville, 1998)

The adoption of ‘good practice’ in the use of representations by teachers and in textbooks. According to (Hearnshaw, 1994) this involves:

- starting any sequence of representations with the most regular, geometrically simple forms available. This will enable students to ‘get their eye in’;
- using as full a range of modes/sub-modes of representation as is possible, introducing them deliberately, systematically, and steadily. This will encourage students to engage their knowledge of the codes of representation;
- maximizing the salience of shapes, edges, shadings, and patterns, within any representation. This will enable students to distinguish the structure of the representation.
- using a range of degrees of illumination for different sections of the representation. This should enable students to more readily perceive contrasts;
- making the full use of colour effects, in terms of saturation, hue, and lightness, of a full range of blues, reds, and greens. Again, this will maximize contrasts.

The use of specific teaching techniques. (Tuckey & Selvaratnam, 1993) identified three approaches, initially within the subject of chemistry but capable of generalisation across the sciences. These involved the use of:

- stereodiagrams. These consist of pairs of drawings or photographs, one giving the view of a representation as it would appear in the left eye and the other as it would appear in the right eye. The illusion of a three-dimensional image is produced viewing these two images with a device such that the right eye only sees the right-eye view and the left eye only sees the left-eye view.
- teaching cues. All diagrams, including the virtual mode, that purport to show three-dimensions (virtual or pseudo-3D representations), do so by the use of specific cues e.g. the overlap of constituent entities, the foreshortening/extension of lines of show below-surface/above-surface inclination, the distortion of bond angles, the emphasis of the relative size of constituent entities (atoms, ions, molecules);
- systematically teaching rotation and reflection through the use of a series of diagrams.
- the use of virtual representational systems. Investment in ‘Geographical Information Systems’ has been strongly advocated (N.R.C., 2006) (p. 155)

At the level of curriculum design, two approaches seem to have great potential:
The explicit use of multi-media approaches to teaching. Mayer has strongly advocated the use of as many media as possible in teaching, on the grounds that accessing information simultaneously both is verbal and visual forms increases the likelihood of effective learning (Mayer, 1997).

The explicit teaching of the ‘master images’ of which scientific representations are composed (Mathewson, 2006)

If enquiries are to lead to comprehensive explanations for the phenomenon of ‘the visualization of representations’ and to outcomes that enable metavisualization more widely and readily attained, then cross-disciplinary enquiries, perhaps associated with ‘design experiments’, involving natural scientists, cognitive scientists, linguists, educationalists, are called for.

Acknowledgment I am most grateful to Maurice Cheng for his insightful suggestions that were used in the development of this chapter.

References


