10 The Role of Abstraction in Scientific Illustration: Implications for Pedagogy

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> In examining visual messages, as in examining other forms of messages, it is necessary to take into account the hidden assumptions which are inevitably adopted both by their producers and their users.
>
> – MOORHOUSE (1974)

> It is important to clarify the potentialities of the image in communication, to ask what it can do and what it cannot do. . . In comparison with the importance of the question, the amount of attention devoted to it is disappointingly small.
>
> – GOMBRICH (1960)

> There is more to seeing than meets the eye.
>
> – GREGORY (1970)

INTRODUCTION

Illustrations are often seen as a very significant part of educational materials. From the earliest stages of elementary school to the advanced college level, illustrations are used profusely and in many cases may be the most striking feature that distinguishes one set of learning materials from another. In fact, the perceived effectiveness of the illustrations clearly plays an important role in the marketing of many educational materials.

Diagrams, accompanied by text, have been a common means of recording and conveying scientific and technical information since the fifteenth century. While the use of illustrations in more secular texts actually goes back much further in time (Ford, 1992; Robin, 1992), the invention of the printing press in the fifteenth century made these illustrated books available to a large audience. Their availability may have been a major cause of the large

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technological advances between the sixteenth and eighteenth centuries. As McLuhan, the late guru of media theory, said:

> The art of making pictorial statements in a precise and repeatable form is one that has long been taken for granted in the West. But it is usually forgotten that without prints and blueprints, without maps and geometry, the world of modern science and technology would hardly exist (1964, p. 145).

In recent years there has been an analogous advance in the capabilities of graphic technologies, as well as their availability. Technologies, such as animation software, computer-aided drawing, and plotting programs have made the techniques of graphic communication available to an ever growing community of users. Scientific visualization has become an important tool for scientists in all disciplines.

However, given the importance of visual displays in science, there has been little research into this area. There has been research on the use of imagery and mental models in scientific thinking (Brown, 1991), as well as some interesting debate on whether human thinking is visual or propositional in nature. But apart from supporting our notion that imagery plays an important role in scientific thinking and creativity, much of this work is quite peripheral to the issue of how scientific illustrations are used and understood. Verbal propositions, arguments, references, analogies, metaphors, and "ideas" have received much greater attention as constituents of scientific reasoning and rhetoric. This imbalance may be due to the fact that methods for analyzing verbal materials are more developed than those for analyzing pictures. Lynch argues that, the fact that writing is the dominant medium of academic discourse is not incidental:

> While pictorial subject matter is alien to written discourse, and requires a reduction to make it amenable to analysis, written subject matter can be iterated without any "gap" within the textual surface that analyzes it. Nevertheless, visual displays are distinctly involved in scientific communication and in the very "construction" of scientific facts (1991a, p. 207).

Gould argues that this neglect can have serious consequences:

> Iconography comes upon us like a thief in the night—powerful and remarkably efficacious, yet often so silent that we do not detect the influence. Pictorial imagery catches us unawares because, as intellectuals, we are trained to analyze text and to treat drawings or photographs as trifling adjuncts. Thus, while we may pore over our words and examine them closely for biases and hidden meanings, we often view our pictures as frills and afterthoughts, simple illustrations of a natural reality or crutches for those who need a visual guide. We are most revealed in what we do not scrutinize (1993, p. 108).

This lack of scrutiny can cause problems at multiple levels—from the design of incorrect visuals to the causing (or the strengthening or existing) misconceptions in the minds of students.

Misconceptions or Alternative Conceptions

Current research in science education has generated a growing body of evidence showing that students come to science classes with theories about how the natural world works. These theories are generally less coherent, less precise, and less extensive than accepted scientific theories and often hinder students' learning.

These cognitive structures that students have prior to instruction have been variously called misconceptions, alternative frameworks, alternative conceptions, or naive theories (Hewson & Hewson, 1984). A great deal of research has documented alternative conceptions of topics as varied as motion, friction, gravity, heat and temperature, electricity, light, evolution, heredity, etc. A good review of such research is given by Driver, Guesne, and Tiberghien (1985). Research in cognitive science and the history and philosophy of science has produced a general consensus on the nature of science learning that can help in understanding why alternative conceptions occur. As Hewson and Hewson (1984) state:

> The emerging picture is of a learner who actively constructs his or her own meaning by looking for regularity and order in the events of the world. On the one hand, learning can happen only by relating the unknown to what is already known, and thus all learning depends on the prior knowledge of the learner . . . On the other hand, learning involves the active generation of new links between new information and the existing knowledge by the learner . . . each learner generates links between new and old for him or herself, it is not surprising to find that different learners construct alternative conceptions of the same phenomena (p. 12).

Most of the misconception research has focused on textual materials. There is little research on how scientific images can hinder or enhance the development of such misconceptions. This paper offers a framework for further research into this area.

Misconceptions and Scientific Illustrations

The scope and applicability of previous educational research into illustrations is limited primarily due to the narrow band of ideas that were considered amenable to scientific questioning. There are two good reviews of research into scientific illustration, a 1979 paper by Fleming and a 1984 book by Goldsmith. In reviewing the work of the previous twenty years Fleming notes that though research has improved, because it has become more analytical and advances in psychology have contributed to our understanding of these issues, much of the work seems to have only limited relevance to answering any questions about the value of illustrations in assisting science learning.

Goldsmith's book (1984), *Research into Illustration: An Approach and a Review*, is a comprehensive review of the research on the understanding of factors affecting the comprehensibility of illustration. It is interesting, though somewhat depressing, to note the absolute lack of any research into how readers may comprehend (or miscomprehend) illustrations. Most of the research focuses on the formal aspects of illustrations, such as the perception of color, shapes, faces etc. Rarely are illustrations seen within the larger context of fulfilling some specific educational purpose. For example, among the more than 650 books and papers referenced in this book, just one paper mentions some specific subject area (biology). However, a closer perusal reveals that the paper is concerned more with the effect of color on children's pictorial comprehension than with biology. The illustrations used could very easily have been from any other discipline within science.

The Goldsmith book does, however, set forth in great detail all the research on picture perception conducted up to 1984. Though the author admits that the findings of the research are conflicting, there are some interesting conclusions about the perception of images in general that are of interest. The research on children's perceptions is quite exhaustive and can be quite useful to textbook designers and illustrators.

Representations of statistical data, and the misconceptions that it can lead to, have been studied in depth in Tufte's (1983) classic work, *The Visual Display of Quantitative Information*. Tufte points out misconceptions that can arise due to the manner in which data are displayed. Such errors may be deliberate in that the designer or statistician willfully presents the data in a manner meant to mislead the reader, or they may be unplanned.

Some of the more interesting work in this area has been done by psychologists of art. Critics such as Ernst Gombrich and Rudolf Arnheim have combined a deep understanding of art and illustration with the psychology of perception to develop theories of how people see and understand art, caricature, and illustrations. Their work is of great relevance to the scientific illustrator and educator. Unfortunately, their work has been largely ignored by educational researchers, and that is a sad commentary on the exclusive nature of intellectual boundaries.

Another approach that has gained prestige and following in recent years is that practiced by the people studying the "sociology of scientific knowledge" (SSK) (Ashmore, 1989). They see illustrations as just one of the many forms of scientific representation and study it within a large societal and discourse matrix. The distinction between what the psychologists of art and the sociologists of science can tell us is an interesting one. The psychologists focus on the more formal and perceptual elements of visuals, while sociologists stress the process of science and knowledge formation, and how that process affects visual representation. Knowledge of both the elements and process is essential if we are to understand how people "read" illustrations.

Following this rather extended introduction, the rest of the paper is devoted to developing a broad framework for studying the manner in which images are used in communicating science. I begin first by looking at the psychology of art and perception. This is followed by sketching out what the sociology of science approach has to say about how scientific representation functions within scientific discourse. Finally, I focus on seeing how these two very different perspectives can help us understand scientific illustration specifically within an educational context.

Psychology of Art and Perception

There are two different approaches to how pictures are interpreted. According to the standard view, a picture is defined in structural terms as, "any two-dimensional artifact that attempts a veridical representation of an object or the relationships between objects" (Reid, 1990). Theorists in this camp see picture interpretation skills in terms of the development of more general cognitive, linguistic, and psycho-motor skills. Pictorial representation depends upon visual correspondence or "likeness" with the object depicted.

Usually pictures are supposed to represent reality—directly. The word "horse" is an arbitrary sequence of phonemes. Any other sequence of phonemes would have done as well. However with respect to images, it is felt, that there is no such randomness. An image is iconic, i.e. there is a one to one mapping between the object with its image.

The other camp (Gombrich, 1960, 1982; Arnheim, 1969, 1974; Gregory, 1970, 1973), however, postulate abilities more specific to the process of "picture interpretation" and attribute the advancement of picture "reading" skills to the learning of pictorial conventions. One can trace the roots of this contentiousness to disagreements about the nature of pictures themselves. While the former position sees development in picture interpretation skills as the increasing ability to make intelligent judgments about pictures which have "imperfect fidelity" with the object depicted, the latter explains progress by postulating a growing vocabulary of pictorial symbols and conventions (see Figure 1). Implications of the second view are that some pictorial conventions need more learning than others and some illustrations pose difficulties because they make greater use of conventions than others. The second view has become increasingly popular especially due to studies into the history of art and the psychology of perception (Gombrich. 1960; Gregory, 1970).

Figure 1. Perception as Hypothesis Testing: A Perceived Object Is a Hypothesis, Suggested and Tested by Sensory Data. A Single Line Can Serve Many Purposes.

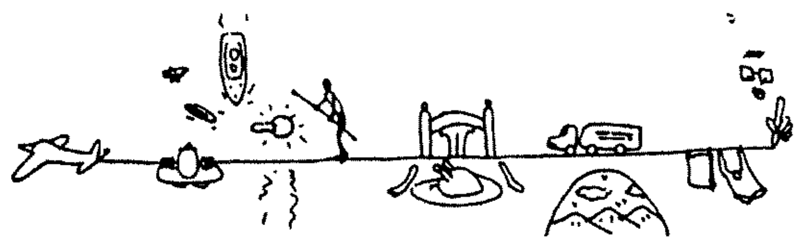


Illustration by author, based on work by Saul Steinberg.

According to this perspective, seeing is not tacking different interpretations to one and the same precept. The experienced physician, mechanic, or physiologist looking at a wound, an engine, or a microscopic preparation "sees" things the novice does not see. If both experts and laymen were asked to make exact copies of what they see, their drawings would be quite different. Perception involves "going beyond the immediately given evidence of the senses": this evidence is assessed on many grounds and generally we make the best bet, and see things more or less correctly. But the senses do not give us a picture of the world directly; rather they provide evidence for checking hypotheses about what lies before us. Indeed we may say that "a perceived object is a hypothesis, suggested and tested by sensory data" (Gregory, 1970).

There is a great commonalty between the views espoused by the psychologists of art and some contemporary post-positivist philosophers of science. Prominent among them is Russell Hanson (1965) with his emphasis of the idea that all observation is theory laden. According to him, there are indefinitely many ways in which a constellation of lines, shapes, patches, may be seen. Why a visual pattern is seen differently is a question for psychology, but that it may be seen differently is important in any examination of the concepts of seeing and observation. As Gregory (1970) puts it, "Perceiving and thinking are not independent: 'I see what you mean' is not a puerile pun, but indicates a connection which is very real." Similarly interpreting illustrations is also a creative task. Illustrations also have pasts and futures; they change and influence each other, and have hidden aspects which emerge under different conditions.

However, perceiving illustrations is, in a very fundamental way, different from perceiving the world around us. Pictures are not natural. Gregory contends that no eyes before man's were confronted by pictures. Previously, all objects in themselves were important or could be safely ignored. But pictures, though trivial in themselves, mere patterns of marks, are important in showing absent things. Biologically this is most odd since for millions of years animals had been able to respond only to present situations and the immediate future. Pictures, and other symbols, allow responses to be directed to situations quite different from the present; and may give perceptions perhaps not even possible for the world of objects. This is their strength, yet it may be where they can go wrong as well. Gregory states:

> Pictures have a double reality. Drawings, paintings, and photographs are objects in their own right, patterns on a flat sheet, and at the same time entirely different objects to the eye. We see both a pattern of marks on paper, with shading, brush strokes or photographic "grain", and at the same time we see that these compose a face, a house or a ship on a stormy sea. Pictures are unique among objects; for they are seen both as themselves and as some other thing, entirely different from the paper or canvas of the picture. Pictures are paradoxes (Gregory, 1970. p. 128).

The paradoxical nature of pictures is that they must convey information about a three-dimensional world through marks on a two-dimensional

surface. There are various ways of doing this, as a survey of world art will show, and almost no two ways are alike. For a long time art historians felt that geometrical perspective was the right way of representing the world. However, geometrical perspective was unknown until the Renaissance. In the highly developed world of the ancient Egyptians, heads and feet are shown in profile, never foreshortened by perspective, which offers a certain resemblance to children's art. Chinese drawing and painting curiously goes against the formal rules of perspective in that lines actually diverge with increasing distance. As Gombrich (1960) says, "It is an extraordinary fact that simple geometrical perspective took so long to develop—far longer than the wheel or fire—and yet in a sense it has always been present for the seeing" (p. 143). But he asks, "Is perspective present in nature? Is perspective a discovery, or an invention of the Renaissance artists?" The answer he suggests is that perspective is an invention, an invention whose implicit conventions we now take for granted. He argues that all art and representation depends on a series of conventions and to place one over the other may be wrong. Geometric perspective may be appropriate for the way the image of the world is formed on the retina, but it need not be the way we actually perceive. "When an artist employs geometrical perspective he does not draw what he sees, he represents his retinal image." Representational realism is not a static phenomenon. Artistic realism includes an abundance of painterly techniques and stylistic conventions which do not simply fall in line along a continuum from "non-realistic" to "completely realistic" (Gombrich, 1960, p. 144). Scientific realism is no different, and scientists use artistic conventions and techniques for documenting observations and illustrating texts.

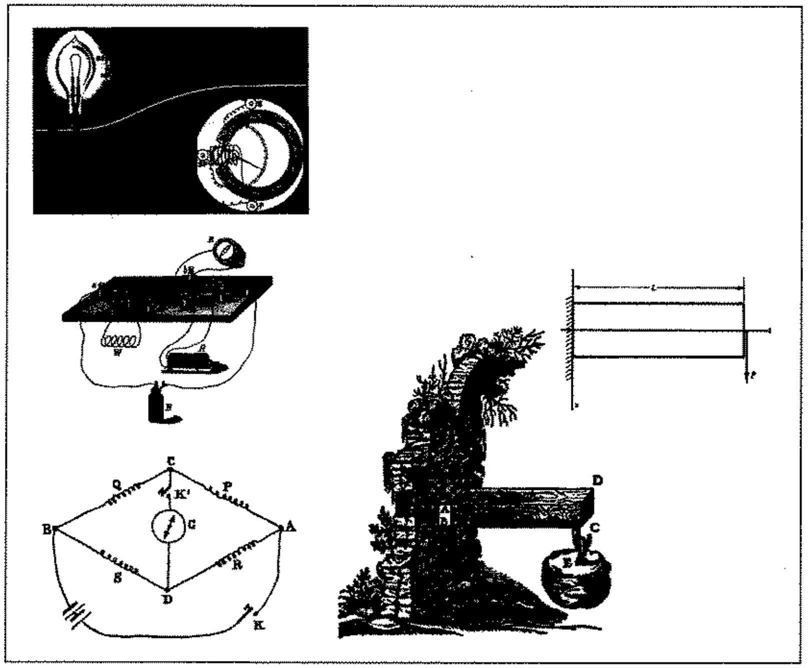
This notion of abstraction and the creation of symbol systems (visual conventions) is of crucial importance in the argument that Arnheim and Gombrich are making. Winn argues that diagrams use "notational" symbol systems. Winn says that "in notational symbol systems an unambiguous relationship exists between each symbol in the diagram and the object to which it refers. Some diagrams contain hierarchies of symbols and symbol groups that illustrate domains of reference at varying levels of complexity" (1993, p. 163).

The symbols used for electronics since the beginning of this century parallel the development of the pictograms of ancient languages. At first the symbols were realistic drawings of the components. Within a few years, the electronic "pictograms" became simpler: the emphasis was placed on the functionally important features of the components, while the outward shapes were lost. The symbols pictured their functional significance. Each symbol is a kind of abstract cartoon. An early (1884) drawing of a Wheatstone bridge circuit shows that the components are drawn as they appear, without emphasis on their functional characteristics. A later (1890) drawing of the same circuit is somewhat more stylized, with emphasis on the functional features of the components. A still later (1898) drawing shows that by this time the components are not drawn as they appear: they are drawn with conventionalized symbols. But such symbols are meaningless to those with no understanding of, in this case, electrical theory (see Figure 2). Symbols only have meaning for those who share perceptual hypotheses, or abstract theories.

Another example, this time from biology—human anatomy to be specific—is given in Miller (1978). Anatomical textbooks give the misleading impression that everything in the chest is immediately distinguishable. In the illustrations, the heart is artificially distinguished from its vessels by a bold graphic outline and sometimes a special color. The aorta is printed in scarlet, the great veins in sky-blue, the nerves are usually represented in green and yellow (see Figure 3). Miller says:

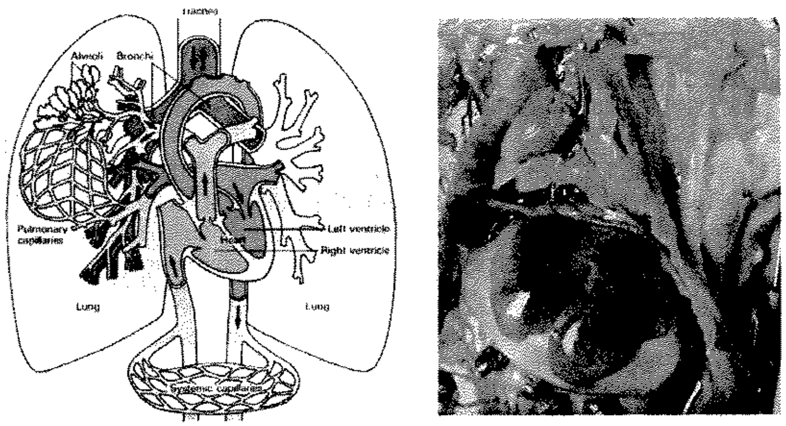
> The unsuspecting student plunges into the laboratory carcass expecting to find these neat arrangements repeated in nature, and the blurred confusion which he actually meets often produces a sense of despair. The heart is not so clearly distinguished from its vessels as the textbook implies, and at first sight the vessels are practically indistinguishable from one another. A practiced eye can readily recognize the gristly pallor of an artery as opposed to the purple flabbiness of a vein, but what

FIGURE 2. Abstract Symbol Systems: Symbols Only Have Meaning for Those Who Share Perceptual Hypotheses, or Abstract Theories.



Wheat-stone bridge diagram as represented in 1888, 1890, and 1898 and Cantilever beam as shown by Galileo and as depicted in today's textbooks.

FIGURE 3. Abstraction and Reality: Anatomical Textbooks Give the Misleading Impression that Everything in the Chest Is Immediately Distinguishable. Diagram of a Human Heart Along with Actual Photograph



> makes the eye practiced are the theories or presuppositions which direct its gaze—and one of the leading theories of anyone now looking into the chest is one which says that arteries are different because the blood flows through them in different directions. The color-codes which illustrate students' textbooks are not simply vivid illustrations of what there is to be seen, but graphic conventions which illustrate theories about the functions of what there is to be seen (p. 177).

The psychology of art approach tells us that there are artistic conventions that have to be learnt in order to understand pictures. These conventions are not "natural" but rather are creations of time and culture. However, scientific illustration is more than art. The term scientific graphics is the marriage of two very different notions, science and art, often felt to be antithetical to each other. Arnheim (1969) sees artistic activity as a form of reasoning, in which perceiving and thinking are indivisibly intertwined. Noting similarities between art and science, he feels that both are "bent on the understanding of the forces that shape existence, and both call for an unselfish dedication to what is. Neither of them can tolerate capricious subjectivity because both are subject to their criteria of truth. Both require precision, order, and discipline because no comprehensible statement can be made without these." However, there are significant differences especially in the criteria of exactness as applied to both disciplines. In a scientific demonstration, the particular appearance of what is shown matters only to the extent to which it is symptomatic of the facts.

> The shape of the containers, the size of the dials, the precise color of a substance may be irrelevant, Similarly, the particular proportions, angles, colors of a diagram may not matter. This is because in science the appearance of things are mere indicators, pointing beyond themselves to

> hidden constellations of forces. The laboratory demonstration and the diagram in the textbook are not scientific statements but only illustrations of such statements. In the arts the image is the statement . . . The arts tell the student about the significance of direct experience and of his own response. In this sense, they are complimentary to the message of science, where direct experience must be transcended and the individual outlook of each observer counts only to the extent to which it contributes to shaping the conception of the phenomenon under investigation (Arnheim, 1969, p. 132).

All scientific illustration has to chart this line between the Scylla of scientific abstraction and the Charybdis of visual specificity of illustrations. This is one level at which misconceptions can occur in scientific illustrations. Students may see a visual in specific terms, as referring to something unique when the concept being dealt with is a more general one. As Lynch (1991b) says:

> Even when a picture obviously resembles an object, just how it does so can be far from obvious when the picture is viewed in isolation. For instance, a picture of a seagull inflight can variously be used to illustrate the aerodynamics of flight, to display the characteristic field marks of a particular species or age-class or gull, to exemplify the basic anatomical features of birds, to demonstrate techniques of nature photography, or to give a pictorial inventory of typical constituents of a shoreline habitat. An appreciation of the picture's conceptual and documentary functions can be gained only when one places it within a cross-referential network. This network includes various other textual features—captions, headings, narratives, and other tables, graphs, photographs and pictures—as well as the practices within which these textual features have a role. The polysemous properties of pictures are readily grasped when one flips through an illustrated text and examines the pictures while covering-up the captions (p. 204).

This is similar to what Gould (1993, p. 211) says while describing the problems with biological illustrations. One of the problems, he feels, is the fact that by intending to "capture the entire time period" illustrators are forced to wedge in as many animals and ecosystems within a single picture as they possibly can. This leads to a false view of prehistoric life, showing it to be more active and crowded than it really was. This is a misconception, since "at most natural moments at most places nothing much is happening."

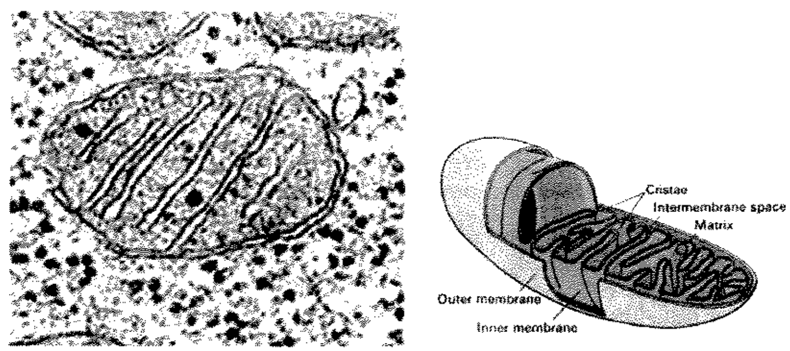
The Sociology of Scientific Knowledge

In contrast to the psychologists of art, the sociologists of science reject (at least temporarily) the idea of representation from an individualistic cognitive foundation, and attempt to "replace a preoccupation with images on the retina . . . with a focus on the 'externalized retina.' . . . [Pictures are used] as evidence of methodic practices, accomplished by researchers working together in groups, which transform previously hidden phenomena into visual displays for consensual 'seeing' and 'knowing'" (Lynch, 1991a, p. 206).

A similarity of viewpoint can be seen in recent developments in "distributed cognition." (Salomon, 1993). This view reexamines the traditional view that sees cognition as existing solely "inside" a person's head and attempts to consider social, physical, and artifactual surroundings in which cognition takes place. The claim is that a "clearer understanding of human cognition would be achieved if studies were based on the concept that cognition is distributed among individuals, that knowledge is socially constructed through collaborative efforts to achieve shared objectives in cultural surroundings, and that information is processed between individuals and the tools and artifacts provided by culture" (Salomon, 1993, p. 14). According to this framework, illustrations, diagrams, and other visual displays must be considered as carrying information within a context contingent on the history and social practices of the domain under consideration. A newcomer into the field may not "see" the same thing since a sharing of concepts has not taken place. Thus it is the business of the educator and the illustrator, to take care of the preconceptions of the students.

Lynch (1991a, p. 217) argues that there is more to the "transformational process" in the creation of diagrams than mere simplification and abstraction (as argued by the psychologists of art). This process synthesizes form as well. Most importantly, it strives to identify in the particular specimen under study "universal" properties which "solidify" the object in reference to the current state of the discipline. In comparing photographs to diagrams of the same object, he argues that while a photograph is "unique, situationally specific, perspectival, and instantaneous" a diagram is "essential, synthetic, constant and veridical." It could be said (quite counter-intuitively) that, within the context of a given scientific discourse, a photograph is an imperfect representation of an actual object, while a diagram represents it more faithfully (see Figure 4). Thus the conventions of representation are more than artistic devices, they take their authority from previous experience and the state of

FIGURE 4. Abstraction Defines Reality: Within the Context of a Given Scientific Discourse, a Photograph Is an Imperfect Representation, While a Diagram Represents It More Faithfully. Photograph and Diagram of a Mitochondrion.



the scientific field to competently build on a body of assumptions about the represented structures.

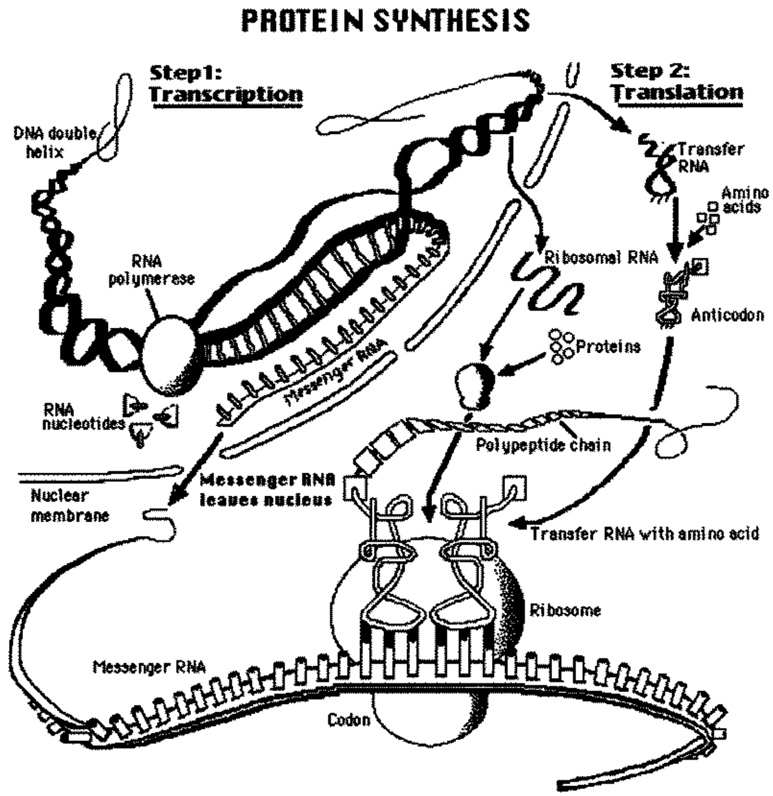
The variety of illustration styles used in scientific communication (such as diagrams, photographs, sketches, tables, graphs, instrumental displays, animations, simulations, and so on) are not isolated representations, but they all work within a framework of verbal and written discourse. Although many sketches and pictures can easily be seen to resemble a familiar object of interest (a cell organelle, animal, or plant, of a particular species etc.) what a picture "is doing in a textual representation is not disclosed by naming what it resembles" (Lynch, 1991a, p. 217). Many diagrams take the form of "conceptual models" of, for instance, a flow of ions across a membrane, a cycle of biochemical transformations, or a molecular sequence. At times such images include symbolic, iconic, and even fantastic features; for example, vectors, cartoon figures, chemical formulas, and labels. Such hybrid combinations of "schematic, pictorial and verbal constituents" make up what Gilbert and Mulkay call "working conceptual hallucinations." (see Figure 5)

A historical approach to graphic conventions in science can reveal which conventions change and which persist, and whether the meaning of persistent conventions remains constant. Many graphic conventions have survived centuries of change in both scientific practice and technology of pictorial reproduction. Some of "these conventions have so much and such enduring power that they can be deployed to effect, and can also pass unremarked" (Gould, 1993, p. 109). O'Hara's (1991) investigation into some of these "invisible" conventions in nineteenth century biological illustration shows a strong emphasis on the geometric ideal of order portrayed through symmetry and numerical regularity. Maienschein (1991) reports similar findings in his work on illustration style in E. B. Wilson's work on cytology *The Cell*. He traces an increased abstraction in Wilson's use of diagrams from the first publication in 1896 to the last publication in 1925. Moreover, he also notices "an enduring premium on symmetry." These conventions are "hardly neutral" and embed within them certain ideas and notions that may not even be apparent to scientists and designers themselves. Hanson (1958) said that one cannot remove the context (speaking of the context in very general terms) from the image: "The context is part of the illustration itself. Such a context, however, need not be set out explicitly, Often it is 'built into' thinking, imagining and picturing. We are set to appreciate the visual aspect of things in certain ways" (Hanson, 1958, p. 15).

Illustrations have a history. Often they are copied and passed on without thought. Illustrations once created develop a life of their own and are repeated indiscriminately in spite of changes in scientific theories. Ford (1992) documents how illustrations have changed over time, sometimes due to improvements in technology, sometimes due to plagiarism.

> The thousand words that a picture is supposed to tell are a small part of the tale. There are hidden influences and cultural pressures underlying what people choose to illustrate, and fashionable constraints on how they make their representation. . . . Plagiarism has been rife in science since the discipline emerged. . . . Each generation of copying takes one further from reality. A living specimen, well portrayed, becomes wooden and stiff as it is copied and re-copied. Scientific realities mutate: six-pointed snowflakes become eight-pointed, [something that just does not exist in nature] just as carefully delineated bacteria transpose themselves into species that seem to exist only in textbooks . . . there are "icons" that stand out in scientific literature: illustrations to attract respect for learning, but which cannot be intended to represent reality. Scientific illustration may be scientific in nature, but it may be far from scientific in application. (p. 164)

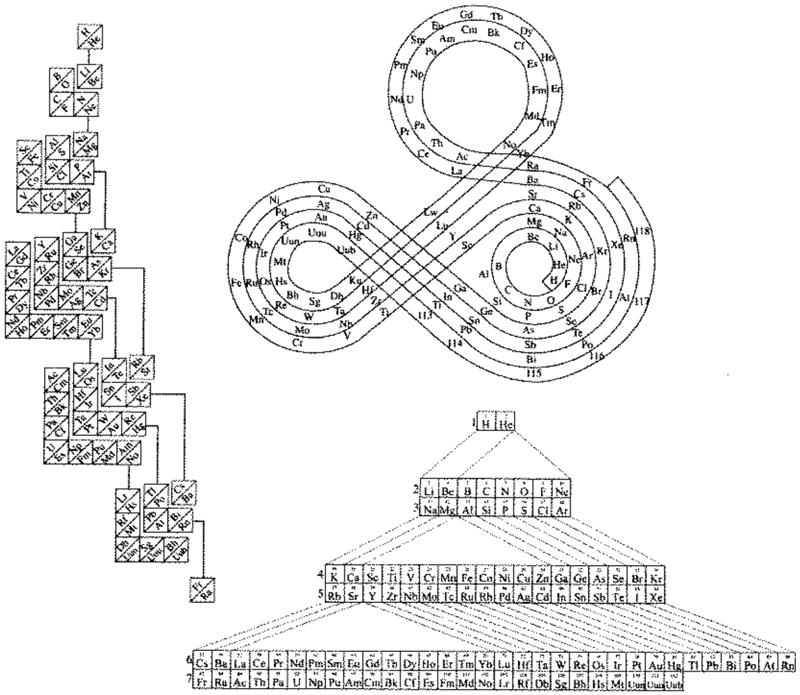
FIGURE 5. Conceptual Hallucinations: Hybrid Combinations of Schematic, Pictorial, and Verbal Elements Make Working Conceptual Hallucinations. The Process of Protein Synthesis.



There may be a feeling that such plagiarism and hidden influences may have existed in earlier more imperfect times, but do not take place today. However, these factors are so deeply ingrained that it may be impossible to even feel their presence except in hindsight. Gould in his chapter on dinosaur iconography shows the changes that have been taking place in pictorial representation of dinosaurs over the last few centuries. Scenes of predation, the staple of Victorian iconography are replaced by scenes of herding and caring. Dinosaurs are no longer slow lumbering giants but rather are sleek, fast, efficient animals. Commenting on these changes Gould says, "I am intrigued to note how closely the trends in prehistoric iconography match the winds of change labeled 'postmodernism' in so many other fields from literature to architecture—so we are once again taking part in a general social movement, not merely following the local norms of science by responding to improvements in factual knowledge." (Gould 1993, p. 109)

Another example of scientific illustrations copied indiscriminately and thus restricting other interpretations is given in a Mazurs (1974) book in which he documents some 450 different ways the periodic table has been portrayed in the past 100 years, all of them "correct" yet different from each other (see Figure 6). Most people however, know just one version of the periodic table, the Mendeleev version. These multiple representations of the periodic system have been used as a basis for developing a multi-media hypertext for teaching complex concepts in chemistry (Mishra & Nguyen-Jahiel, 1997;

FIGURE 6. Missing Representations: Some Alternative Representations of the Periodic System Not Usually Seen in Textbooks. From Left: Treptow's Atomic Table; Janet's Spiral and Pyramid Table.



Mishra, 1998). As Root-Bernstein (1989) says in his book on scientific discovery and creativity:

> Pictures, tables, graphs can be dangerous things. Revealing one point, they hide assumptions, eliminate possibilities, prevent comparisons—silently, unobviously. Thus, a pattern makes sense of data but also limits what sense it can make (p. 142).

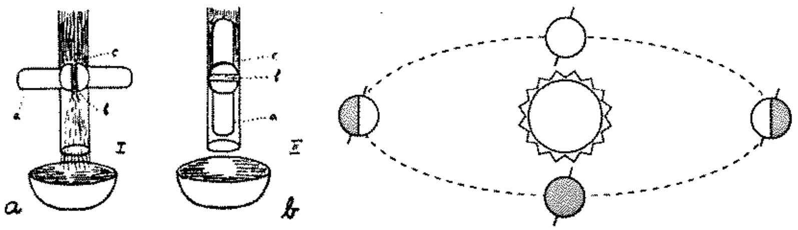
The reasons for this conservatism on the part of artists and scientists are many—ranging from lack of knowledge about other interpretations to political, social, and personal factors that abhor change. The conservative nature of the publishing industry (with economic pressures to stick to the acceptable and proven) are also issues to consider.

Misconceptions and Scientific Illustrations: Revisited

It must be obvious that despite apparent differences there are certain fundamental similarities between what psychologists of art and the sociologists of science have to say about the use and perception of images. However, we must remember that science is a very broad term and is used to describe a large variety of practices and products. The word "products" is used in a very general way as the specific result of scientific activity. It may be a theory, a host of data, a new piece of technology, and so on. It does not necessarily mean some specific material object. Different subdisciplines in science need different strategies and "ways of doing." If we are to understand how illustrations can lead to misconceptions it is important to focus on individual topics in science. It is important for us to ground our theoretical work in the actual educational situation. Misconceptions in science do not happen independent of the content of what is to be taught and learned. Each situation will be unique in the way in which it affects students and their prior beliefs.

One of the first references to these issues of misunderstanding illustrations is given by Arnheim (1969). He shows a figure that was used by Piaget to test the comprehension of children (see Figure 7). Do they understand how a tap works? When the handle is turned horizontally, the canal is open and lets the water run through; otherwise it is closed. The child's performance will largely depend on whether the drawing is recognizable as a tap. The pipe, flat rather than cylindrical, hangs in space. It does not continue on top, nor does it receive water from anywhere. The hatching does not indicate liquid filling a hollow and shows little relation to the dark stripe, meant to be the canal. The canal is in front of the handle rather than behind it, and the handle is not in front of the pipe. Does *b* show a vertical handle outside a pipe or rather a kind of bob, swallowed by a rectangle or possibly a tube? As Arnheim (1974) says, "But surely, if a child passes the test he does so in spite of the drawing, not with the help of it; and if he fails, he has not shown that he does not understand the working of a tap. He may simply be unable to extricate himself from a visual pitfall" (p. 120).

FIGURE 7. Illustrations as Visual Pitfalls: The Illustration of a Tap as Offered by Piaget and Standard Illustration of the Earth-Sun System.



Deficient pictures of this kind can be found at any level of abstractness. The drawings could be much more realistic and still be unsuited to present the relevant features of the physical situation. They fail not because they are not lifelike or devoid of detail but because they are ambiguous and misleading.

The next example is based on Gould's (1993) analysis of fossil iconography. He feels that the artistic conventions used in these paintings/illustrations create an enormous departure between scenes as sketched and any conceivable counterpart in nature. He sees a fundamental difference between artistic genres in general and the nature of fossil iconography in specific. All artistic genres follow social conventions, but few also "grapple with the assumption that finished products represent a natural reality" (p. 108). Gould identifies a series of conventions (all of which can be defended) that "distinguish painted fossil scenes from inferred actualities." He argues that certain fundamental misconceptions that many people have about evolution can be traced to these conventions.

Another example is related to astronomy. Most people seem to have consistent misconceptions about how the seasons are caused. The standard belief is that seasons are caused by the elliptical nature of earth's orbit around the sun. The further the earth is from the sun the colder it gets and vice versa. It is summer when the earth is closest to the sun and winter when it is furthest away. However, this theory does not explain why the southern hemisphere switches seasons with the northern hemisphere nor does it explain why we do not have two winters and two summers every year. It is provocative to think of this misconception as being caused by the standard illustration seen in textbooks and science writings. The orbit of the earth is described as being "shaped like a stretched out circle" (quoted in Michaels & Bruce, 1989). However, they ignore the fact that the ratio between the major and the minor axis of the ellipse that is the earth's orbit is so close to unity that no diagram (at least one that fits in a regular textbook) can show its elliptical nature. This is compounded by the way in which these illustrations are usually drawn—from a viewpoint above and at an angle over the plane within which the planets lie. This point of view exaggerates the elliptical nature even more. Michaels and Bruce enumerate a few more "problems":

> The distorted scale in the figure presents the sun as smaller than the earth (when in fact the sun has 100 times the diameter of the earth). It shows the earth/sun distance as less than one earth diameter, when in fact it should be 100 times the diameter of the sun. These representations may contribute to the misconception that variations in energy received between the poles and the equator are due to differences in distance to the sun (p. 7).

CONCLUSION

To conclude, visual representations are powerful tools to communicate ideas. However, in spite of their effectiveness and importance very little research has been focused on how they work in an educational situation. This paper identifies three areas that are possible "danger areas" for students. The first is that all forms of illustration depend on artistic conventions—conventions that are not "natural" and have to be learnt. Students unaware of these conventions can easily misunderstand illustrations and other visual representations. Second, apart from artistic conventions, scientific illustrations function within the matrix of science, with its hidden assumptions and biases. Quite often these biases are invisible to us at this moment in time and thus are quite insidious in their effect. Illustrations in a given domain are very dependent on the theory they are based on. This is not a one way street—a theory helps us "see" certain facts and then illustrate them; and these illustrations, in turn, support the theory. And third, illustrations have a contingent, zig-zag history and their copying and recopying leads them to evolve far from what they began with—any diagram of amoeba or a paramecium in school-textbooks can show this "evolution." (See Ford, 1993, for some excellent examples.) Apart from the above factors, we must also consider the fact that illustrations are treated (created/read) differently by different domains or subdisciplines within science. Biological illustrations have a very different look and feel from tracks of subatomic particles or from geological maps. Even within biology, genetics requires a different kind of visual skills than paleontology. Thus, understanding how illustrations work in science cannot be done in a generalized manner, it must be grounded in the dynamics of a specific discipline.

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