KATHLEEN M. FISHER

INTRODUCTION

Mapping Biology Knowledge addresses two key topics in the context of biology, meaningful learning and the role of knowledge mapping in promoting meaningful learning. Chapter 1 provides an overview of several common strategies for spatial knowledge representation, Chapters 2–6 discuss some of the key considerations in learning for understanding, and Chapters 7–10 describe several metacognitive mapping tools and the research that informs their use.

Please note that the chapters are written in different voices and thus have different styles, tones and ways of referring to the authors, depending upon the particular authorship of each chapter. A brief description of the chapters is given below.

Road maps are regularly used by travelers on land, sailors use their charts when they go to sea, and scientists often rely on spatial knowledge maps when they practice science. Science maps range from the long-established periodic table (now available in many delightful and useful forms as internet hypertext documents) to biochemical pathways to the newer human genome maps. Likewise, semantic or word-based knowledge maps are often used by students, teachers and researchers as learning, teaching, knowledge navigation, and assessment tools. *Chapter 1, Introduction to Knowledge Mapping* by Fisher, provides an overview of word-based knowledge mapping including concept maps, cluster maps, webs, semantic networks, and conceptual graphs.

The domain of biology is vast, the depth of knowledge in many areas is awesome, and the knowledge structure of the field is both complex and irregular. In addition, biology knowledge is assimilated from many different sources, both formal and informal. For these and perhaps other reasons, knowledge mapping seems to be particularly useful for those interested in mastering biology. These issues are examined in *Chapter 2, The Nature of Biology Knowledge*, by Wandersee, Fisher and Moody. This chapter also considers the "two cultures" influencing biology education, scientists and science educators.

In many biology courses, students become so mired in detail that they fail to grasp the big picture. Overemphasis on detail accounts in part for the fact that relatively few Americans understand how trees "construct themselves from thin air" (Schnepps, 1997b), even though nearly all have studied photosynthesis at least once and often several times. Yet memorizing trivial detail is not a goal of science learning. A more useful approach is for the learner to construct a well-ordered overview of the big ideas and their interrelations, combined with skill in knowing how to find more information as needed. *Chapter 3, Knowing Biology* by Wandersee and Fisher, describes a little-known *system analysis* of biology as one example of a high-level overview (Miller, 1978). It presents the human mind as an expectation-generator that will hold onto information it perceives valuable for anticipating future events and that will discard information it perceives as irrelevant. The "need to know" principle can be helpful in deciding the level of detail students must have in a given situation.

It is now well established that students' minds are not blank slates and that students' preconceptions or naive conceptions can present major impediments to learning. This is especially true in a field like biology where there is a lot of folk knowledge and personal experience. *Chapter 4, Student Misconceptions in Biology* by Fisher and Moody, reviews this widely researched phenomenon.

Meaning-making is achieved in part through mindful learning, the use of fluid and flexible thinking. *Chapter 5, Meaningful and Mindful Learning* by Fisher, reviews Langer's (1989, 1997) seven myths of education, including ideas such as overdrilling (rote learning) and "work now, play later." This chapter prompts teachers to examine their commitment to "coverage" of "facts" at the cost of meaning-making and development of thinking skills.

Most of our thoughts lie below the surface of conscious awareness, just as most of an iceberg is submerged beneath the sea. And just as only the tips of icebergs are visible to us, so only the tips of our thoughts are available to conscious knowing. And to carry the analogy one step further, just as an iceberg sunk the unsinkable *Titanic*, so subconscious thoughts can sink or at least subvert a lesson. This is the topic of *Chapter 6, Language, Analogy, and Biology* by Wandersee. This chapter concludes the examination of meaning-making, looking at how biology jargon and analogies can help or hinder understanding.

Metacognitive tools serve as support systems for the mind, creating an arena in which we can make our knowledge explicit, reflect on its organization, and polish its edges. These tools are also useful for building and assessing students' content and cognitive skills. Concept circle diagrams are metacognitive tools that can help students build their skills in categorizing, which is essential to constructing knowledge hierarchies and to learning complex information. This topic is presented in *Chapter 7, Using Concept Circle Diagramming as a Knowledge Mapping Tool* by Wandersee.

If you want to see where you have been and where you are going, get a map. This advice is as basic for students learning science as it is for travelers on the road. *Chapter 8, Using Concept Mapping as a Knowledge Mapping Tool* by Wandersee, describes Novakian concept maps. The chapter is organized using Frequently Asked Questions (FAQs).

Ideally, just as we can look into a mirror to see our faces, so it would be nice to gaze into a clever machine to examine our minds. Unfortunately, this clever machine has yet to be developed. However, the SemNet® software provides a crude approximation, allowing us to see explicitly see how we and our students think about a given topic at a given point in time. *Chapter 9, SemNet® Semantic Networking* by Fisher, provides an overview of the SemNet® tool in the classroom.

Textbooks are integral components in biology teaching and learning. Mapping tools can be used by readers to increase their access to the content of a text and by writers and other interested people to analyze the structure of a text. *Chapter 10, The*

Paradox of the Textbook by Moody, provides a historical overview of biology texts and illustrates one approach to analyzing the importance of a topic, in this case evolution, in texts over time.

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CHAPTER 1

Overview of Knowledge Mapping

If You Want to Find Your Way, Get a Map!

> Sara and Charlotte, driving from Cincinnati to San Francisco, leave the freeway in Colorado and soon realize they are lost. Sara, who is driving, asks Charlotte to get out the map so they can find their way again.
>
> Susan and Roy, exploring the islands of the Caribbean in a Catamaran, get blown off course by a storm and aren't sure where they are. They take a reading on the GPS and pull out a chart to find their location.
>
> Adam and Paul, taking a biochemistry course in college, find themselves hopelessly lost in the voluminous new material. They sit down over a weekend and map out where they have been and where they are going in the course, and return on Monday in much firmer control of their destiny.

WHAT IS KNOWLEDGE MAPPING?

Knowledge mapping or knowledge representation is a process in which a schematic representation of knowledge is created. Knowledge maps typically include the most important concepts (usually noun ideas) in boxes, ovals, or circles (Figure 1.1). Concepts are usually connected by lines which are often unlabeled (and thus represent mere associations, as in "is somehow related to") and are sometimes given name labels. When the lines (links, relations, arcs) are labeled, it is usually with a verb phrase. The relationship indicated by a line between two concepts is always bidirectional, but the name label that is shown on a map may be either unidirectional or bidirectional. Arrowheads are often included on the line so the reader knows which way the relation should be read, but in hierarchical maps, arrowheads are often omitted on the assumption that the reader will read from top to bottom.

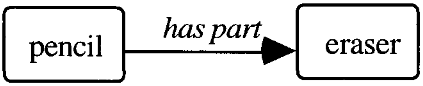

Figure 1.1. Elements of knowledge mapping include concepts such as pencil and eraser, links such as "has part", and propositions such as "pencil has part eraser".

It appears that knowledge mapping has originated independently multiple times and in multiple contexts. As one example, a young woman who recently worked for me had invented knowledge mapping on her own, as a tool for learning. To the best of her knowledge, she had never heard of or seen knowledge maps created by others. Her maps were hand drawn in rich colors, similar to the Mind Maps and Visual Thinking Networks described briefly below. Additional discoveries of knowledge mapping are described below.

A BRIEF HISTORY OF KNOWLEDGE MAPPING

Knowledge mapping began early, when cave men and women sketched their knowledge about their environment in the form of symbols on the walls of caves. We'll skip much history between these early events and modern times. The history presented below makes no effort to be comprehensive, but instead captures some of the highlights of knowledge mapping in education of particular interest to us.

According to Brachman and Levesque (1985), knowledge representation as a means of creating artificial intelligence (AI) in computers began in the 1950s. Specifically, they cite a 1950 paper by Turing and Shannon (1950) and a conference at Dartmouth in 1956 as the starting points for serious work in AI. The goal of AI is concerned with "writing down descriptions of the world in such a way that an intelligent machine can come to new conclusions about its environment by formally manipulating these descriptions (Brachman and Levesque, 1985, p. xiii). AI requires much more elaborate mapping techniques than those desirable in education.

The goals of knowledge mapping in education are quite different from those in AI. Educational knowledge mapping is seen primarily as a tool for learning, teaching, research, intellectual analysis, and as a means for organizing knowledge resources. In all fields using knowledge mapping, the idea is to tap into the workings of the brain. AI and education are two sides of a coin. AI wants to use knowledge mapping to build computers that mimic the brain's intelligence, while educators want to use knowledge mapping to stimulate and support students' efforts to increase their intelligent use of their own innate resources.

Gordon Pask developed many forms of cybernetic knowledge mapping in the 1950s through the 1970s, during which he published at least three books and 150 papers. His interest in mapping was applied to studies involving such topics as the "Styles and strategies of learning" (Pask, 1976a) and "Conversational techniques in the study and practice of education" (Pask, 1976b). He developed maps to represent the ideas that emerged in student conversations and to show the connections between those ideas (Pask, 1975, 1977). Since researchers today are once again turning to discourse and dialogic analysis, it seems likely that they will also find knowledge mapping helpful.

Pask straddled the worlds of AI and education, as indicated by his dual appointments as Professor in the Department of Cybernetics at Brunel University and Professor in the Institute of Educational Technology at the Open University, both in Great Britain. These two topics are combined in his 1975 book, *Conversation, cognition and learning: A cybernetic theory and methodology*. In the introduction, Pask describes his theory as being concerned with psychological, linguistic, epistemological, ethological, and social mental events of which there is awareness – that is, conscious thoughts and interactions. He was obviously ahead of his time, at least in education. But researchers today might appreciate the many strategies he developed for mapping the dynamics of a conversation.

In the same decade but on a different continent, science educator Novak and his graduate students invented concept mapping as a learning tool for K–12 students (Stewart, Van Kirk, & Rowell, 1979). Novakian concept maps grew out of Ausubelian learning theory (1963, 1968) with its emphasis on building connections between ideas. Novakian concept maps (described further in Chapter 8) are widely used in science teaching today from elementary school through the university.

With the advent of the Macintosh personal computer in the early 1980s, Fisher, Faletti and their colleagues created the SemNet® knowledge mapping software as a learning tool for college biology students (Fisher, Faletti, Patterson. Thornton, Lipson & Spring, 1987, 1990). The major objective was to help students shift from their prevailing rote learning methods to meaningful understanding of biology content. The design of this software grew directly out of AI and cognitive science, especially Quillian's (1967, 1968, 1969) semantic network theory for how we store information in long term memory (see Chapter 9 for more information).

Also in the 1980s, Wandersee (1987) developed concept circle diagrams (CCDs) for the purpose of helping students clarify their thinking about inclusive/ exclusive relationships. Being able to organize ideas into categories and to distinguish between similar but different things are key steps in learning and are supported by the use of CCDs (discussed in Chapter 7).

In the late 1980s and early 90s, Horn (1989) in the US and Buzon (e.g., Buzon & Buzon, 1993) in Great Britain took knowledge mapping into the business world. In fact, Buzon has been a tireless promoter of his strategy, Mind Mapping, in both education and business arenas throughout the British Empire. Buzon is interested in mapping as a means of promoting creativity and divergent thinking, and has developed the MindMan software to support his style of mapping (Table 1.1). Probably the best commercial success in knowledge mapping, at least in the US, is the Inspiration software (Table 1.1), a concept mapping tool available for both IBM and Macintosh platforms.

In the late 1990s we have witnessed the amazing growth and blossoming of the World Wide Web. The quantity of information available at our fingertips is staggering, and the need for intelligent, user-friendly mapping strategies grows stronger every day. So far, this need has not been adequately answered, although various efforts are being made (see, for example, Table 1.1).

Table 1.1. Some knowledge mapping software described on the internet, 1999

Software	World Wide Web Site
The Axon Idea Processor	http://web.singnet.com.sg/~axon2000/article.htm
Banxia Software	http://www.banxia.co.uk/banxia/
CoCo Systems Limited	http://www.coco.co.uk/
Inxight Hyperbolic Trees	http://www.inxight.com/Content/7.html
Inspiration Software	http://www.inspiration.com/
LifeMap	http://www2.ucsc.edu/mlrg/lifemapusermanual375/lifemapusermanual375.html
MindMan Software	http://www.mindman.com/
SemioMap Builder	http://www.semio.com/download/Download.cgi
SemNet Software	http://trumpet.sdsu.edu/semnet.html
Smart Ideas	http://www.smarttech.com/smartideas.htm
VisiMap	http://www.coco.co.uk/prodvm.html

HOW DOES KNOWLEDGE MAPPING HELP STUDENTS LEARN?

Research suggests that in more cases than not, knowledge mapping exercises of all types help students learn. Why is this? There are many possible answers to this question. First, mapping provides sustained support for *time on task* in thinking about a topic. Second, if mapping is done collaboratively, it can lead to *extended discussions about the meanings of concepts and the relations between them.* Third, the act of creating an organized structure of ideas on paper or in a computer necessitates and often *prompts the creation of such a knowledge structure in the mind.* Fourth, knowledge mapping prompts students to *take implicit, often fuzzy, associations and make them into explicit and precise linkages*, a process that is at the heart of meaning-making. Fifth, knowledge mapping *takes many cognitive and metacognitive skills that remained invisible for so many generations and makes them visible, explicit, and accessible.* Sixth, mapping prompts students to *make finer discriminations between ideas*, another process at the heart of learning. Seventh, the more one practices, *the better one becomes at organizing and relating concepts* (Cliburn, 1990). And eighth, each time two concepts are joined with a relation in working memory, *that information is believed to be "broadcast" to all the modules in the brain* so it can be used to solve any current problem the vast subconscious brain may be working on (Baars, 1988).

Jonassen, Beissner, & Yacci (1993, p. 8–10) describe the advantages of knowledge mapping in another way. First, they say, semantic structure is inherent in all knowledge. Second, structural (organized, semantic) knowledge is essential for recall and comprehension. Third, learners assimilate structural knowledge effectively. Fourth, knowledge structures in memory reflect the world. Fifth, structural knowledge is essential to problem solving. And sixth, there are significant differences between the structural knowledge of novices and experts, so that for novices, working on their structural knowledge to make it more expert-like is a natural part of learning.

HOW CAN KNOWLEDGE MAPPING CONTRIBUTE TO EDUCATIONAL REFORM?

Mapping is a tool for personal and social knowledge construction and a tool that supports meaningful learning. In the classroom, mapping can provide

- structure for the *minds-on* part of *hands-on/minds-on* teaching,
- a systematic means for reflecting on and analyzing inquiry learning,
- a knowledge arena for operating on ideas, and
- tangible support for the transition from teacher-centered to student-centered classrooms.

WHAT IS THE EDUCATIONAL REFORM MOVEMENT?

Serious educational reform began in the 1970s in Great Britain and Australia. In the early 1980s the US came on board. The momentum of reform has steadily gathered steam ever since.

The reform movement advocates meaningful science learning at every grade level. The group in the American Association for the Advancement of Science (AAAS) that is working toward reform is called Project 2061, to signify their expectation that it will take that long (until the year 2061) to revamp education in the US. AAAS has produced several well-known guidelines to help the process along (1983, 1989, 1998), and has succeeded in bringing the two cultures (scientists and science educators) together to work on the project. The National Research Council (1996) also has taken a leadership role, as have many other professional and granting agencies.

Among other things, reform documents (Appendix 1.1) repeatedly cite the need for strategies that help science learners acquire interconnectivity and discrimination among science ideas, two features that most clearly differentiate novices from experts and most dramatically affect recall and application of knowledge. It also happens that these two features especially benefit from knowledge mapping activities. Cohen (1991, p. 46), in studying a newly reformed mathematics classroom, describes the problem succinctly:

> If the recent reforms are to succeed, students and teachers must not simply absorb a new body of knowledge. Rather, they must acquire a new way of thinking about knowledge and a new practice of acquiring it. They must cultivate new strategies of problem solving that seem to be quite unusual among adult Americans. They must learn to treat knowledge as something they construct, test and explore, rather than as something they accumulate.

One obstacle to achieving reform is that many teachers are confused or overwhelmed by the demands of teaching science for understanding (Flick, 1997). They understandably mix many of their old teaching strategies with the new (Cohen, 1991). Further, American schools have not been organized to support continued growth and learning by teachers (although this is changing slowly and in piecemeal ways). Teachers lack the basic requirements of a professional workplace such as a work station and telephone, and they are not given work time to prepare their lessons

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CHAPTER 2

The Nature of Biology Knowledge

Genetic Drift?

Twelve faculty members in a major university's genetics department were collaborating to produce a televised genetics course. Unexpectedly, they discovered that they were unable to agree on the definition of a gene — the basic unit of their field. How could that be? With so many experts and a rather well-understood entity, how could there be so much dissension about what a gene is?

WHAT IS INVOLVED IN "KNOWING BIOLOGY?"

The problem that the geneticists in the opening vignette were facing is not necessarily an unusual situation. Although an outsider might be startled by it, insiders will not be. A biologist's biology knowledge, like all knowledge, consists of various kinds of mental representations — declarative and procedural, logical and emotional, experiential and received, private and public, semantic and structural, basic and applied. The twelve geneticists each had their own specialization, so each knew different parts of the genetics subdomain. Each one viewed genetics through the lens of his own preparation, experience, and specialization. Each had also learned his genetics at different times, under different conditions, and in different ways. Disagreements such as this are generally more common among specialists than among generalists – in part because of the details associated with learning a particular subfield in depth, and in part because of the experts' deep emotional attachment to their own hard-won views of the subject matter.

Not only do specialists view their subject through different lenses, but a study by one of the authors (Abrams & Wandersee, 1995) finds that expert ideas about biology knowledge change over time. Beginning biologists typically believe that biology knowledge is derived solely from observations of the living world, as shown in Figure 2.1.

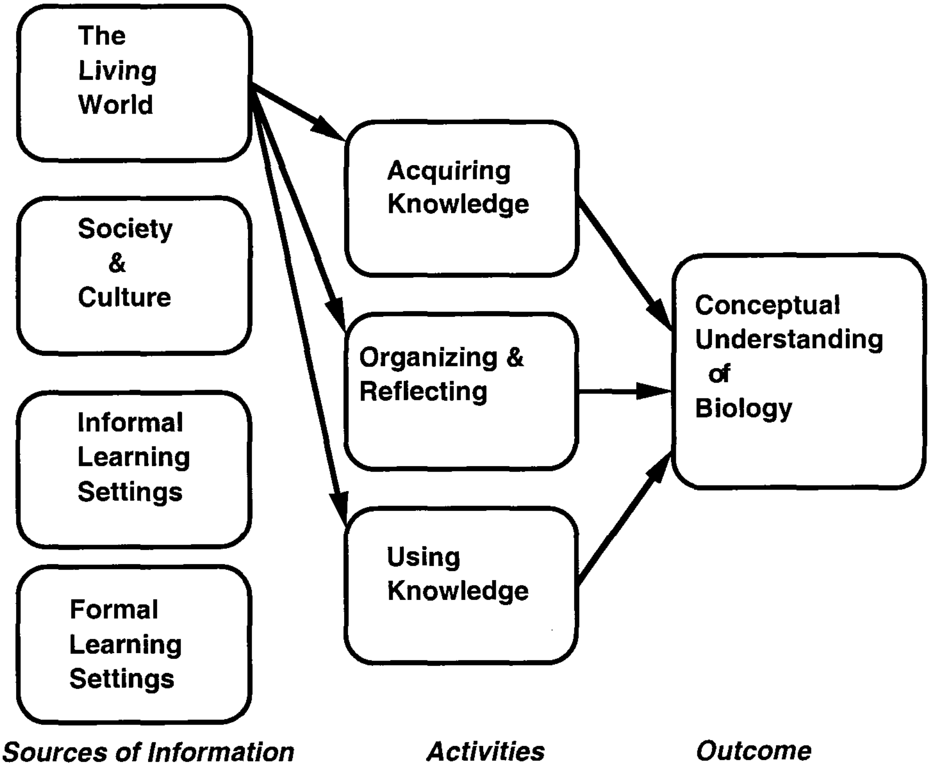

Figure 2.1. Naive view of sources of information influencing biology knowledge. Adapted from Wandersee, 1996.

Gradually, however, practicing biologists come to realize that what we already know affects how we see, acquire, organize, and use new biological knowledge, and even how we perceive and interact with the living world (Figure 2.2).

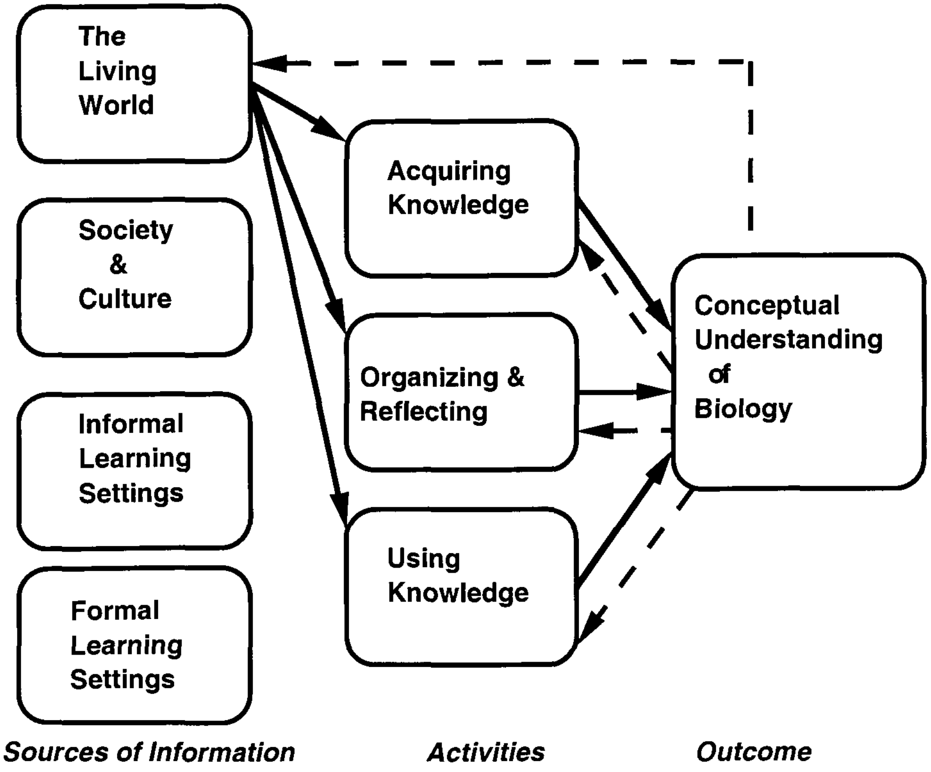

Figure 2.2. Recognition that what we know about biology influences what we see.

But even this is not the whole picture. While the living world is obviously the most pertinent source of biological information, our conceptual understandings of life (and the conceptual understandings of our students) are inevitably influenced by secondary sources such as society, culture, informal learning, and the theoretical constructs we derive from our formal learning (Figure 2.3). Our basic assumptions about what is likely, what is possible, and what is impossible are derived from attitudes and values we develop from these background sources over a lifetime. This is called one's worldview following Joseph I. Lipson (1980, personal communication; see also Cobern, 1996). Worldview may enable individuals to be receptive to certain new ideas or closed to them.

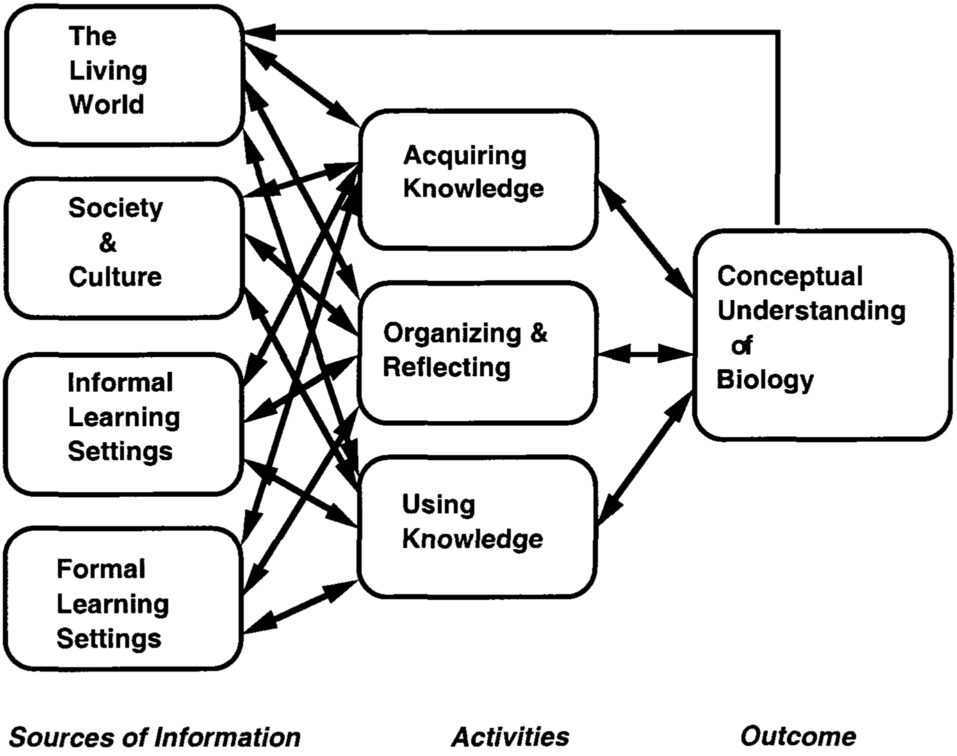

Figure 2.3. A more sophisticated view of learning: Recognition that our cultural assumptions, metaphors for understanding, and overall worldview influence what we see. Modified from Wandersee, 1996.

THE NATURE OF BIOLOGY

The word "biology" originated in the 19th century. The precursors of this broad field of study were natural history, botany, and medicine, including anatomy and physiology (Mayr, 1982, p. 36). Darwin's theoretical and evidentiary legacy, coupled with Mendel's work, unified all of biology and established its explanatory power (Atrans, 1990). Molecular biology and the "modern synthesis" extend the powers of explanation and in some cases allow prediction. Neo-Darwinian evolutionary thought informs our understanding of ultimate causality, while detailed elucidation of DNA gives valuable insights into the proximal causes of cellular control as well as elucidation of phylogenetic relationships both currently and throughout evolutionary time.

Biology is the study of living things. But what are living things? Is all life cellular as claimed by the cell theory? Or are our intimate noncellular parasites, the viruses, also alive as some argue? And if so, are prions alive? And when does human life begin? At conception? At the onset of neurophysiological activity? At birth? Or is life simply continuous, passed on from cell to cell? Is a person actually dead when her brain stops functioning or when her heart stops beating? Likewise, is the tomato we've just picked up from the grocery store alive? If we slice that tomato, is the slice alive? If we take a seed from that slice, is it alive? And is a cluster of naturally root-grafted White Pine trees really a single super-organism (Kourik, 1997)?

Defining life is not a simple task. Life's boundaries remain much "fuzzier" than we'd like in spite of (or perhaps because of) the many recent advances in our knowledge. Its fuzzy edges are just one of the ways in which the life sciences differ from the physical sciences. The contrasts range from the nature of the objects and events being studied to what counts as an explanation. The form and content of theory and the generalizability of explanations are also significantly different in the life sciences (Rosenberg, 1985, p. 34). Thus, like Ernst Mayr (1982), we respect the physical sciences but do not aspire to become them. Biology is a gradually maturing science, but that does not mean it is simply on its way to becoming more like physics and chemistry. As one example, the levels of organization that characterize life on earth (atom, molecule, cell, tissue, organ, organ system, organism, population, community, ecosystem, biome, and biosphere), each with its own emergent properties, have no close parallels in the physical sciences.

Biologists study objects that have (and vary in) information content and whose history matters, whereas chemists typically study inanimate objects such as atoms and molecules that are essentially interchangeable. Life consists of open systems of a certain minimum complexity. These systems self-regulate, self-repair, maintain a steady state, develop, reproduce, and are seriously constrained by their requirements for survival (Miller, 1973, p. 69). The dynamic, synthesizing, organizing, energy-consuming nature of living things sets them apart from inanimate objects.

John Moore holds that evolution, genetics, and developmental biology are "the core of conceptual biology," because these subdomains focus on "the fundamental characteristic of life — its ability to replicate over time (1993, p. viii)." From the organism's genetic program, to the differentiation that occurs as a single cell becomes a multicellular organism, to the enhancement of the survival of the species that natural selection confers, life has ancestry that cannot be ignored.

Bronowski's Rule (Bronowski, & Mazlish, 1960, p. 218) claims that confidence in any science is proportional to the degree to which it is made mathematical. This rule may be appropriate for the physical sciences, but is not broadly applicable in biology, even though some subfields (e.g., cell physiology, genetics, ecology) make use of mathematics. Another difference is that "The objects with which physical science deals do not have goals, ends, purposes, or functions (except as they serve explicit human purposes)" (Rosenberg, 1985, p. 43). Limb buds in a chick embryo, in contrast, do have developmental goals programmed into their DNA. Under normal circumstances, limb buds consistently and eventually become wings. For these and other reasons, the living and nonliving worlds are profoundly different.

In summary, biology is a unique science, quite different from the physical sciences. Biology knowledge is extensive, highly complex, incomplete, and often ill-

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CHAPTER 3

Knowing Biology

Is Blood Type Related to One's Character?

In contemporary Japan, knowing a person's blood type is not just considered important during blood transfusions, it is also used to predict an individual's personality and the nature of his or her social interactions (Sakurai, 1997). Young people who go out on a first date typically try to learn each other's blood type—or, ask their own matchmaker to screen out the undesired types in advance. Employers in Tokyo may seek to hire only employees who have a particular blood type—one socially compatible with the employees they already have. People who read the Japanese tabloids hope to discover what blood types their favorite TV and film stars have. Women's magazines even publish diets said to be suitable for particular blood types. In Japan, the subject of blood types is as popular a topic of general conversation as the weather.

From the history of biology, we know that many so-called common sense ideas have turned out to be erroneous when subjected to the light of careful scientific scrutiny. Human blood, for example, has been attributed with having extraordinary powers far beyond the role we ascribe to it today as a physiological fluid in the form of a liquid tissue – with past claims including that it acts as the seat of the soul, as the prime determinant of human inheritance, and as the controlling agent of human personality.

With respect to the latter, Hippocrates promoted blood-letting methods to adjust human personality characteristics using the doctrine of the four humors (Gardner, 1972, p. 58). Thomas Bartholin (1616–1680) "reported that he had examined a young girl who displayed feline characteristics after drinking the blood of a cat" (Magner, 1979, p. 116). Even that giant of biological thought, Charles Darwin, proposed a blood-borne theory of inheritance in which tiny gemmules that were given off by every body cell were carried to the reproductive organs and assembled into eggs or sperm (Magner, 1979, pp. 409–410). Darwin thought that, at conception, blood-borne gemmules arising from both parents formed the new human embryo – with gemmules for particular traits coming from either the maternal or paternal line.

While the possibility always exists that blood-based explanations of human personality may someday prevail in science, their future looks bleak at this juncture. From what we know about inheritance of personality today, claiming linkage patterns between ABO blood type genes and personality-influencing genes seems far-fetched as a comprehensive explanation. Some proponents claim that the very fact that today's science rejects their views only substantiates how progressive their views really are. However, as the popular scientist Carl Sagan (1979, p. 64) pointed out in his writings about borderline science, while it is true that people sometimes laugh at those whose thinking is actually far more advanced than their own, such laughing alone is not convincing validation – since people also laugh at Bozo the Clown, and rightly so.

The arbiter in science is convincing and replicable evidence. Until it exists, speculation must be treated as speculation. The big contribution which a scientific theory makes is bringing order out of chaotic facts and observations; while the ABO blood-type theory of personality does that to some extent – it must also fit with the biological knowledge we currently have about human blood and about human personality's heritable and environmental components. Social science tells us that personality differences go well beyond biologically defined temperaments. Prevailing moods may reflect long-term positive or negative experiences – they may derive from each individual's personal and social learning history within particular familial or cultural contexts (Snow, Corno, & Jackson, 1996, p. 258). In short, human personality determination is apparently quite complex and has multiple causes. Perhaps it is well to recall Alfred North Whitehead's oft-quoted aphorism, "Seek simplicity, but distrust it."

The idea that ABO blood type influences personality dates back to 1930 when, during Japan's Asian military invasions, the Japanese military commissioned a study of how blood type affects personality — in an attempt to create better soldiers. Some proponents have sought anthropological data to support these claims. Yet there seems to be little scientific evidence to support the conclusion that ABO blood type influences personality and few other cultures share this belief. Is it fact or fantasy?

The idea still persists in Japan today – across all age segments of the population. The Japanese believe that type A blood (the "farmers" type) produces nervous, detail-oriented, honest, loyal, careful accommodators; type B blood (the "hunters" type) produces noisy, proud, aggressive, optimistic, adventurous people; type AB blood (the "humanists" type) produces creative, critical but useful people who are full of contradictions; and type O blood (the "warriors" type) produces highly motivated, workaholic, emotional people who seek to control any group they join.

What can we learn about blood types from biology? In 1901, Karl Landsteiner reported that there were types of human blood that together constituted the ABO blood system, and that the incompatibility of certain blood types could explain the rapid intravascular hemolysis that occurs during some blood transfusions. In 1930, he received the Nobel Prize in medicine for his discovery of human blood groups. The ABO blood types are produced by a single gene for which there are three different alleles (variations of the gene) in the population. These alleles produce enzymes that modify carbohydrates attached to the surface of red blood cells. The carbohydrates are antigenic — that is, they can stimulate production of antibodies and will react with antibodies that are specific to them. Today, we know that there are many other blood group antigens on red blood cells, the most important of the others being the Rhesus (Rh) system. There is also a complex set of antigens (the HLO antigens) on white blood cells and many other body cells.

As for the ABO system, we now know that the A, B, and O factors are carbohydrates (oligosaccharides) that attach to the ceramide lipids of the red blood cell's plasma membrane, but that can also attach to proteins. Type O cells are marked with a saccharide sequence — fucose-galactose-n-acetylglucosamine-galactose-glucose — attached to the ceramide membrane lipid. The A antigen is produced when N-acetylgalactosamine is attached to the outer galactose in this sugar, while the B antigen is produced when an extra galactose is attached to that outer galactose. Thus, what humans inherit is either 1) an allele coding for an enzyme that attaches N-acetylglactosamine to the O saccharide (type A), 2) an allele coding for an enzyme that attaches an extra galactose to the O saccharide (type B), 3) both of these alleles (type AB), or 4) two alleles that do not alter the basic saccharide (type O) — see Figure 3.1.

Humans produce antibodies that circulate in the blood and that react with type A and type B antigens. A type A person will have anti-B antibodies, a type B person has anti-A antibodies, and a type O person has both kinds of antibodies. Interestingly, these antibodies are produced in response to antigens found on intestinal bacteria, but react with type A and type B red blood cells due to cross-reactivity. The antibodies are not produced if an antigen is part of "self." Most people do not make antibodies that react with the type O saccharide. Recently, however, some rare individuals have been discovered who do produce antibodies that react with the O saccharide — the Bombay phenotype.

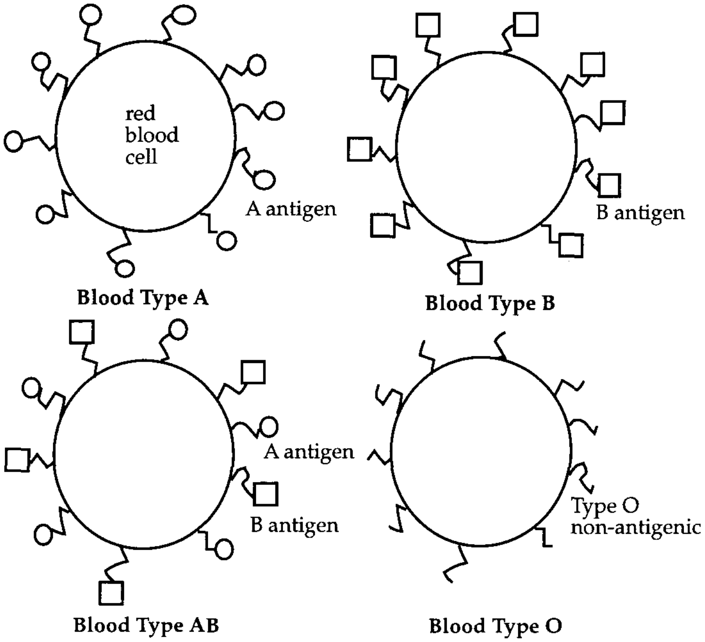

Figure 3.1. Schematic diagram of glycolipids on the surface of red blood cells that are produced by ABO alleles and give rise to the ABO blood types. Drawing by Laura Becvar.

What does this ABO cell biology have to do, if anything, with human character determination? Seemingly nothing. Science is mute on this point, and there is virtually no scientific evidence to support an "ABO personality hypothesis." It is interesting to note that the Japanese blood type study was mandated in the same year that Karl Landsteiner won the Nobel prize, which may be why this particular red blood cell system (ABO) was selected as the scientific tool to use for human personality prediction. Yet while blood typing *is* scientific, such simplistic and unwarranted leaps of application definitely are not.

Humans seem to have strong desire to predict personality — it is part of their future orientation. In the US astrology serves this purpose, while in Japan the ABO blood system is used. Science cannot support either approach because there is no theoretical basis, no known mechanism, and questionable empirical data.

On the other hand, scientists must always reserve final judgment. Consider the recent National Institutes of Health findings showing success in treating certain medical conditions using the traditional Chinese therapeutic technique of acupuncture, or the recent Baylor College of Medicine pilot study showing that magnetic therapy (using small, 300- to 500-gauss magnets fitted to the anatomic area where the pain is centered) successfully reduces pain in patients suffering from post-polio syndrome (Altman, 1997). Both therapies initially seemed dubious to scientists, and unfortunately they still don't understand the scientific basis for these therapeutic effects. Right now, two leading hypotheses for the magnetic therapy include the following: the magnets may increase blood flow to a painful area of the body – reducing inflammation and pain, or, the magnetic field may effectively block pain receptors in the painful area (Fremerman, 1998, p. 56). These therapies contrast with many other popular remedies for medical conditions that have been shown to be ineffective.

Such topics are not typically the foci of scientific research because scientists are more likely to make progress via studies that are supported by and have the potential to advance sound scientific theories. Scientists are justifiably reluctant to work on investigations in the so-called *borderline* or *fringe areas* of science. They are willing to pass on studies with a low probability (albeit, potentially high yield) for success, those that require hypotheses which cannot be supported by current scientific theory. The Japanese blood type theory of character determination and the popular astrological approaches to forecasting human events fall into this category. Today the scientific research topics being pursued are determined mostly by where the funding is available, but since scientists are involved in establishing the funding programs, the same biases still apply, albeit indirectly.

HUMANS SEEK TO INTEGRATE THEIR KNOWLEDGE FOR FUTURE USE

The foregoing story illustrates that advanced societies expect science to be able to explain everything—even social behavior. But, science has its limits (both as to what constitutes a legitimate scientific question and as to what is currently explainable scientifically). Science doesn't have all the answers and never will. It is likely that individual human behavior will always remain unpredictable to some degree. The leap from basic biology to behavior is enormously challenging, in that it entails many levels of biological organization, environmental factors, and the effects of learning from experience.

In spite of these reservations, we agree with psychoanalyst George Kelly (1955, p. 48) who maintains that humans ultimately seek to anticipate real events. Such anticipation is crucial for survival of the individual and the species. Humankind is future-focused. In fact, Kelly says that humans are "tantalized" by the future and this is why we argue that humans' knowledge structures reflect this bias.

People search for recurrent events and the conditions under which they occur. The relations humans use to connect the concepts that they have already learned serve primarily to represent reality for future reference and application; relations make possible the conceptual hierarchies that serve to "rank-order" and integrate what we know for efficient use later. Dennett (1996, p. 57) puts it this way, "A mind is fundamentally an anticipator, an expectation-generator." The process of knowledge mapping is useful in this regard in that it helps us to make our relations explicit and to streamline our knowledge structures for ease of retrieval.

THE IMPORTANCE OF THE "NEED TO KNOW" PRINCIPLE

It appears that some organisms have little need to know things in advance. The amoeba does not seem to have a plan or even a focused "search image" of what it must seek out or avoid. It responds to selected stimuli "on the fly." An economy-of-information rule seemingly applies across the kingdoms of life—although the quality and quantity of what needs to be known in advance varies with the species. Thus, each extant species of organism has, over time, developed perceptual and representational limits adequate for its survival to date.

This is not necessarily so for contemporary humans. As "informavores," we have, quite recently in our history, been led to think that more information is always better than less. Unfortunately, such a superabundant stimulus flux can also lead to what has been called "information overload" and "paralysis of analysis."

We suggest that in biology teaching and learning, students' knowledge structures should be optimized primarily for efficiency and effectiveness in making anticipatory decisions. Many complex details that probably will not be used frequently in the near future can be "off-loaded" to external memory devices (e.g., books, computer storage devices, or visual media). Dennett (1996, p. 134) points out that such off-loading can free us from the processing limitations of our brain—which is far from the largest in the animal kingdom — thus, streamlining our thinking.

Biology teachers have traditionally foisted high volume/high conceptual density memorization tasks upon their students—claiming these to be a requirement for "understanding" biology and an indicator of their courses' high academic rigor. (We think that knowledge-mapping tasks would be a better alternative to such assignments—more on this later.) And while these fact-laden assignments are usually not solely rote-memorization tasks, they do tend to induce a high level of rote memorization. Few instructors would want to ask a former graduate to retake her final exam five years hence in, for instance, plant physiology, to see what course-based knowledge is still accessible today. While many students, especially biology majors, are able to memorize and reconstruct selected biology topics in great detail within the context of a particular biology course, biology teachers are generally aware how little of that information each student stores in long-term memory. And the quantity of long-term understanding declines precipitously with nonmajors.

SPURIOUS CRITICISM OF STUDENTS' UNDERSTANDING

Craig (1997, p. 23), in a short essay on how woefully inadequate today's University of Michigan students' knowledge of American historical and political knowledge is, exemplifies the carping of those university professors who apparently have not thought through which knowledge in their field is of greatest worth.

He relates that every semester for the past 10 years, he has given his undergraduate classes on public opinion, consisting mostly of upper class students, a "brief quiz of assorted historical facts." Later he dubs these facts to be "basic historical and political knowledge."

What is this foundational knowledge the "bright, inquisitive individuals" in his class lack? Here are the examples Professor Craig (1997, p. 23) gives. Who are Michigan's two current senators? When did World War II begin and end? Who is the current US Secretary of State? Who was Joseph Stalin? These are factoids—informational tidbits that can be easily off-loaded and retrieved on a need-to-know basis. He does not include a single general principle such as "What conditions generally lead to instability in a country?" or "What are the biggest threats to democracy?"

Craig says he was dismayed to find out that his students were not embarrassed by their performance on his quiz, telling him (Craig, 1997, p. 23) that "they wouldn't need the information in their future jobs" and asking, "When is any of this stuff going to matter in my career?" On the basis of his short quiz and the students' subsequent defensive reaction to being told they had performed poorly on it, he then concludes that these students "see no need to understand why democracy needs to be preserved," closing with a dire warning: "...If our most promising young people have no appreciation for why democracy is worth preserving, how will they know when it is threatened?"

From the information presented in the essay, we side with the students. While a well-read, up-to-date person may have little trouble answering such specific and relatively trivial questions, college students are typically so busy with ample, challenging course work, jobs to pay for their education, and other college-related activities that most must virtually abandon public life during their college career. All of the questions cited have arguably little relevance to the students' immediate future, nor are their answers necessarily representative of the quality of their future citizenship, or even of their overall understanding of American history. While ignorance of dates and surnames is claimed by Craig (1997) to augur the demise of American democracy, we think it actually indicates college students' aversion to courses driven by obsolete views on what constitutes good instruction, and their rejection of educational practices that overvalue memorization and mindless learning.

KATHLEEN M. FISHER & DAVID E. MOODY

CHAPTER 4

Student Misconceptions in Biology

Achieving Understanding

A number of young children were given a log and asked, "Where does the weight of this dry log come from?" They responded, "from the sun, water, the soil, the seed. . ." Harvard and MIT graduates were then asked the same question. Their answers were largely the same as those offered by the youngsters. The university graduates were then asked, "What would you say to someone who said to you that the weight of the tree comes mostly from carbon dioxide in the air?" Among their replies were such comments as: "Really! I would wonder about that. I would wonder how that's possible." "I would disagree because this same volume of air would weigh much less unless it was highly compressed." "I'd say obviously, carbon dioxide is intimately involved in photosynthesis. I'd say carbon is not much of a building block from what I know of biochemistry." "I'd say that's very disturbing and I wonder how that could happen."

A middle school student, Jon, is given lessons about photosynthesis. After the lessons he knows the formula for photosynthesis by heart and is able to write it on the board. When asked what is in the dry log, he estimates that it contains about "70–75% water, and 25–30% other stuff, including bark and minerals from the soil." The interviewer asks if any of the carbon dioxide that goes into the leaves stays in the tree. Jon says, "Uh, maybe a little bit but not too much." His logic is that if oxygen and carbon dioxide had weight, we couldn't breathe; and if these gases have no weight, then carbon dioxide cannot possibly contribute to the weight of a tree.

The interviewer gives Jon a block of dry ice to hold with an asbestos glove and tells Jon that this is frozen carbon dioxide. Jon is very surprised as he realizes the block has weight. The interviewer asks what Jon thinks about the weight of CO_2 now. Jon concludes that solid carbon dioxide might have weight but gaseous CO_2 does not.

Excerpts from Schnepps, M. (1997b).

THE NATURE OF MISCONCEPTIONS

Among the most pervasive features of the terrain uncovered by the cognitive paradigm in science education is the presence among many students (in fact, probably among all people) of active misconceptions about natural events. The "blank slate" model of the mind postulated by Locke (Locke, 1891, 1996) encouraged the easy assumption among educators that students receive instruction as if they were empty vessels, devoid of any ideas of their own.

In fact, we now know that students come to the classroom brimming with ideas about a great many issues and events in the natural world. People are constantly building mental models to make sense of the world around them. Unfortunately, a substantial number of these models are erroneous from the scientific point of view. For example, the common and persistent misconception that carbon dioxide cannot contribute to the weight of a tree has been extensively studied (Haslam & Treagust, 1987; Wandersee, 1984; Anderson, Sheldon & Dubay, 1990; Gravett & Swart, 1997). The identification and description of such naive ideas represents a major stream of activity in science education research.

Within the research community, a profusion of names has been suggested to refer to such conceptions, reflecting the dynamic and unsettled nature of the field. Many investigators prefer the designation 'alternative conceptions,' since it is value-neutral and demonstrates respect for student ideas. Other proposed names range from the simple — "naive ideas," "prescientific ideas," "preconceptions," and "conceptual primitives," to the complex — "limited or inappropriate propositional hierarchies" or LIPHS (Wandersee, Mintzes, and Novak, 1994). The present chapter prefers to adopt an eclectic approach in which varying terms are employed according to their nuances and context. The primary term employed here, however, remains "misconception," selected to underscore the cognitive transformation required in order to achieve the scientific view.

The discovery of the fertile field of students' conceptions suggests a modification to Ausubel's dictum (1963, 1968), "Ascertain what the student knows, and teach accordingly." With the recognition that what the student "knows" consists in part of ideas that conflict with scientific beliefs, Ausubel's admonition might more appropriately be stated, "Ascertain what the student misunderstands, and teach accordingly." This injunction, however, turns out to be more difficult to put into practice than it may at first appear to be.

The purpose of this chapter is to elucidate the nature of preconceptions, and to suggest ways in which mapping devices such as circle diagrams, concept maps, mind maps, and SemNet can be employed as a kind of bridge to enable students to make the transition to the scientific view.

Wandersee, Mintzes, and Novak (1994) have reviewed more than 3,000 studies of misconceptions in science. They distilled eight propositions that represent the consensus of investigators. These are summarized (in a different order from the original) and elaborated upon below.

First, learners come to formal science instruction with a diverse set of alternative conceptions concerning natural objects and events. To a large extent, these alternative conceptions are widely shared, often held by 20% or more of a given student population. Science teachers are largely unaware of the existence of these ideas in students' minds.

Second, the alternative conceptions that learners bring to formal science instruction cut across age, ability, gender, and cultural boundaries. Many similar conceptions are found in students and in the general population worldwide.

Third, alternative conceptions often parallel explanations of natural phenomena offered by previous generations of scientists and philosophers. The fact that these naive conceptions are widely shared across both space and time is a tribute to their sensibility. They are logical conclusions drawn from limited data. Further, they underscore the point that many scientific ideas are counterintuitive. Scientific understandings represent hard-won insights into the workings of the world.

Fourth, alternative conceptions have their origins in a diverse set of personal experiences including direct observation and perception, peer culture and language, as well as in teachers' explanations and instructional materials. They are a product of active sense-making (see also Chapter 5).

Fifth, for the reasons described below, alternative conceptions are tenacious and resistant to extinction, especially by conventional teaching strategies. Where such conceptual conflicts are concerned, students often require compelling evidence – they truly need to be convinced. Simply being told is not sufficient reason for them to dismantle their well-established belief systems. The students' own ideas are so well established and so satisfying to them that they tend to be reluctant to replace them with scientific ideas. The scientific ideas may be rejected because they seem foreign, silly or unbelievable, as well as because of the emotional attachment students have to their own ideas. In other cases, the scientific ideas may be altered or misinterpreted so they can appear to be consistent with the student's ideas.

Sixth, to complicate matters further, teachers often subscribe to the same alternative conceptions as their students. As noted above, nonscientific conceptions are not limited to students; they are as natural to human beings as breathing. We all have them. They occur because most people, scientists included, do not employ the scientific method in their everyday efforts to make sense of the world. Nor do most people have access to the accumulated wisdom of every field. Humans simply draw the best conclusions they can on the basis of what is usually their limited knowledge.

Seventh, learners' prior knowledge interacts in profound ways with knowledge presented in formal instruction, resulting in a diverse set of unintended learning outcomes. Many teachers assume that "I told them, they heard me, therefore they know it." This, in fact, may be the most widespread misconception in education.

Eighth, instructional approaches that facilitate conceptual change are usually essential for replacing a resistant misconception with a scientific idea. Such approaches are generally difficult to discover and time-consuming to implement. But effective conceptual change strategies are at the heart of inquiry-based science teaching and constructivist learning. They are necessary if the American public is going to acquire even a modest degree of sophistication in scientific thought (see, for example, McComas, 1997).

In summary, alternative conceptions are not idiosyncratic or peculiar to individuals or groups of individuals. On the contrary, they are shared across age, gender, and culture, they appear regularly in the history of science, and they occur in the cognitive structures of many adults. Preconceptions are not arbitrary or random explanations for events, but rather represent a pattern of understanding that is plausible to the learner who is attempting to make sense of the world with limited knowledge.

The review by Wandersee, Mintzes, and Novak (1994) enables us to see the fundamental characteristics that are shared by misconceptions. Other resources which summarize research on misconceptions include Helms and Novak (1983), Champagne, Gunstone, and Klopfer, (1985), Novak (1987, 1993), and Pfundt & Duit (1994).

One positive aspect of misconception research is the attention it has brought regarding the absolute necessity for teachers and researchers to be well-grounded in both content knowledge and pedagogical content knowledge. That is, to be good at what they do, researchers and teachers must know at a deep level both the content being taught and the specific strategies useful for teaching that topic, known as pedagogical content knowledge or PKG.

It is also important to recognize that preconceptions are not exclusively obstacles to learning. Since preconceptions often have some predictive power in certain practical situations, Clement (1982a) suggests that they be thought of as zero-order models which can be modified with appropriate instructional strategies.

The fact that both useful prior knowledge and misconceptions exist in abundance is a reasonable and straightforward consequence of personal knowledge construction and strong verification of constructivist learning theory (Pope, 1982; West and Pines, 1985; Clement, 1982a; Collins & Gentner, 1982; von Glasersfeld, 1987; Fisher, 1991; Gunstone, 1994). Students are actively engaged in making sense of the world around them long before they arrive at the classroom door. If many of their ideas about natural processes are naive and contradictory to scientific ideas, that is merely indicative of the fact that the findings of science are often counterintuitive or otherwise not obvious. Indeed, if everything in nature were just as it first appears, science would hardly be necessary at all.

SOME EXAMPLES OF COMMON MISCONCEPTIONS IN BIOLOGY

Few biology faculty are aware of the obstacles their students face in trying to come to terms with even simple biology ideas. The vignette at the beginning of this chapter describes a well-studied misconception that is highly resistant to change – namely, the belief by many people that an invisible gas, carbon dioxide, cannot possibly contribute carbon to growing plants for making sugars, starches, and cellulose. The problem is that a great many people believe that gases have no weight because we cannot feel the air around us. This primitive belief interferes with the learning of many science ideas in addition to photosynthesis, such as changes of state, conservation of matter, and so on.

As another example, one of us (Fisher) finds that up to 20–25% of her college seniors every semester do not understand what makes up the bubbles in boiling water. They claim that the bubbles contain oxygen and hydrogen, or air, or sometimes a vacuum. Convincing the students that the bubbles contain water vapor is no easy task – again, telling is not enough. This conception comes from a lack of understanding of changes of state, conservation of matter, and also from the common belief that you can see water vapor, but when water evaporates it turns into an invisible gas and therefore is not water vapor.

A third example is the difficulty involved in understanding what it means to be alive (Stepans, 1985; Carey, 1987; Tamir, Gal-Choppin, & Nussinovitz, 1981; Brumby, 1982). Young children often think that plants are not living because they are not mobile, and many older students assume that such life forms as seeds are not alive.

DISCOVERING MISCONCEPTIONS

People who first read or hear about misconceptions imagine that they must come tumbling out of students' mouths in every classroom. If this were the case, students' naive conceptions would have been discovered long ago. On the contrary, several factors conspire to keep teachers from ever knowing what students are really thinking. First, students generally have implicit rather than explicit knowledge, meaning that they are not quite aware themselves what they are thinking or what assumptions they are making. Second, students are not encouraged to say what they are thinking in traditional classrooms, so that even when their knowledge is explicit, students learn to keep it to themselves. Third, the opportunities for students to express themselves in nonverbal ways in today's classrooms are severely limited, since so much testing is now multiple choice and short answer. And fourth, teacher-designed multiple-choice tests offer what the teachers consider to be valid distracters, not what the students think. Most naive conceptions are so far removed from the scientific view that it simply doesn't occur to most teachers to include such ideas in their test items.

Identifying and characterizing naive conceptions generally entails considerable effort. One of the most frequently used techniques for eliciting students' ideas is the clinical interview (Pines, Novak, Posner, & VanKirk, 1978; Osborne & Gilbert, 1980; Ericsson & Simon, 1984). Two other frequently used methods described in more detail below are concept maps and multiple choice tests which incorporate common misconceptions as item distracters. Other approaches have used sorting and word association tasks (Champagne, Gunstone & Klopfer, 1985) and computer simulations (Nachmias, Stavy & Avrams, 1990).

DISTINGUISHING MISCONCEPTIONS FROM OTHER ERRORS

There are many different kinds of cognitive errors such as a slip of the tongue (Brown & O'Neill, 1966), action slips (Norman, 1981), and information processing errors (Fisher & Lipson, 1985). These types of errors are usually easily corrected. As noted above, naive conceptions are set apart from these errors in that they are shared by a significant fraction of students; they are surprisingly resistant to being taught away (especially with traditional, didactic teaching methods); and they often appear in similar frequencies in classrooms around the world.

Resistance to change is their most pronounced feature and the one that is most troublesome to teachers. In many cases naive conceptions are so deeply embedded in an individual's conceptual ecology that contradictory information either bounces off or is modified to fit the preexisting theory. The cognitive upheaval that is necessarily

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CHAPTER 5

Meaningful and Mindful Learning

Real Life Can Promote Meaningful Learning!

> Susan's mother, her two sisters, her aunt, and her aunt's daughters had contracted breast or ovarian cancer and three of them, all less than 45 years old, had succumbed to their diseases. For these reasons, Susan decided to have her breasts removed prophylactically. However, cancer researchers had just identified a molecular marker associated with the gene for breast cancer in Susan's family, known to them as "Family 15." The researchers hadn't thought about sharing their findings with the family until they heard about Susan's plans for surgery.
>
> Members of Susan's family had come to believe that a breast cancer gene was being passed from mothers to daughters. Susan thus assumed she would follow in her sisters' footsteps. However, the researchers informed Susan that she didn't require surgery because she did not have the breast cancer gene. Without realizing the bomb they were dropping, they explained that 50% of all family members, males and females alike, would have this autosomally linked gene.
>
> The many family members who had thought they were exempt from the cancer plague went into shock. Anna and Adrienne, two daughters of Susan's Uncle Doug, had assumed their father did not have the gene and thus neither did they. However, they learned within a period of less than 3 intense weeks that a) they may have the breast cancer gene, b) in fact, they did have the breast cancer gene, and c) they not only had the gene, but mammographs revealed that they also had breast cancer! Their previously secure worlds turned topsy-turvy. At the same time, they realized that their newfound scientific knowledge probably saved their lives. (Waldholz, 1997)

This vignette illustrates a mother to daughter theory of inheritance invented by a family under duress. The theory adequately accounted for the cancer cases they observed in their own family during a relatively short period of time, but the data were limited and insufficient. Under dramatic circumstances, family members were informed that the scientific theory was quite different from their own. Compelling evidence (in the form of the unexpected presence of breast cancer in two young women who thought they were safe from the scourge) supported the scientific theory. All 39 family members not only had to discard their "naive conceptions" (described in Chapter 4) and assimilate the new scientific ideas, but they also had to generate new inferences about appropriate ways of managing their lives.

Real life has a way of imposing meaningful learning on us in a highly persuasive manner. Learning and retention are generally increased when adrenaline levels are higher, as in these life and death situations. The classroom is a bit different, however. This chapter looks at the problems of achieving meaningful learning in biology classrooms.

WHAT IS LEARNING?

Learning can be a lot harder than simply absorbing new knowledge. Learners' prior knowledge and background assumptions can present major obstacles. Carefully selected hands-on experiences can serve to challenge such background assumptions and bring new understandings. Such science activities are not an end in themselves, but rather a means to an end – to develop understanding of scientific ideas. In this chapter I aim to clarify and make explicit what we mean by "understanding of scientific ideas," "meaningful learning," and "mindful learning."

Much has been discovered about how people learn in the past few decades, due in part to a convergence of theory and empirical research from many different fields. These findings seem strong because different researchers in different fields using different methodologies have come to similar conclusions. The reform movements currently sweeping educational communities at all levels, especially precollege (briefly described in Chapter 1), are attempting to bring some of this knowledge into the classroom. The goal is to generate the mirror image of how to learn – namely, how to teach.

MINDFUL LEARNING

The *processes* of mindful learning lead to meaningful understanding (Langer, 1989, 1997; Murray, 1997; Gagne, 1977). Mindful learning refers to the ways in which we function during the learning process.

The basic idea is that fluid, flexible thinking boosts our learning ability. Langer encourages us to experiment and to play with information, looking at it from different perspectives, making use of multiple examples, and exploring how the meanings of a given set of information change in different contexts. She identifies seven myths or false attitudes (Langer, 1997, p. 2) that are embedded in the educational system and that stunt students' growth and interest in learning. They are reviewed below.

First, many in education believe that the basics should be so well learned that they become second nature. This is incorrect, says Langer. Drilling in the basics leads to overlearning or learning without thinking – the automaticity described above. Does it make sense, she asks, to freeze our understanding of a skill before we try it out in different contexts and adjust it to our own strengths and experiences? One of the studies performed by Langer and her colleagues found that pianists who learned by varying their playing style performed more competently and creatively than those who learned to play strictly through repetition.

Second, educators think that paying attention means staying focused on one thing. This myth, according to Langer, fails to recognize the value of novelty in holding our attention. Her studies show that varying the target of our attention, whether it is a visual object or an idea, improves our memory of it. In one study performed with

Martha Bayliss, groups were instructed to read short stories. The "mindful" groups were instructed to vary aspects of the story such as to read from different perspectives, consider different endings, etc. The "focus" groups were told to focus their attention on certain fixed aspects of the stories. The control groups read without any specific instructions. When participants were asked to list all they could remember from the story they just read, the mindful groups remembered significantly more details than the others, even though they had the most to think about.

Third, conventional education buys into the idea of "work (learn) now and play later." Langer claims, however, that learning itself can and should be fun. She feels the fun is lost when ideas are removed from their contexts and when learning is evaluated and graded. This shifts the reward from the innate pleasure of learning to the pleasure of getting a desired grade (or the fear or disappointment of not getting the desired grade). The innate pleasure of learning, she says, comes from making finer and finer distinctions between things.

Fourth, rote memorization is prevalent in education, but Langer sees memorizing as a way of taking in information that is personally irrelevant. Rote learning is usually undertaken for the purpose of performing on an evaluation, not to achieve understanding. It is analogous to the twist that occurs in the courts as lawyers set out to win a case, not necessarily to find justice. Langer feels that one way to reduce rote learning is to encourage students to make information personally meaningful.

Fifth, memory is essential to living in the world. It provides the basis for our expectations, actions and safety precautions (e.g., don't put your hand on a hot stove). But, says Langer, forgetting can have its benefits, especially in the opportunities it provides for rethinking ideas in a new context.

Sixth, teachers often act as if intelligence consists of knowing facts. This is not the case, says Langer. Intelligence consists of thinking flexibly and looking at the world from multiple perspectives. This theme, so relevant to biology, has been elaborated by Spiro and colleagues in their cognitive flexibility theory, a theory of knowledge acquisition in ill-structured domains (e. g., Spiro, Coulson, Feltovich, & Anderson, 1988). Although Spiro developed cognitive flexibility theory to describe biology learning by students in medical school, I find it provides an excellent model for teaching nonmajor biology as well (Fisher & Gomes, 1996a).

I believe that when teaching nonmajors or majors who will be working in other fields, emphases on the "big picture" are important. Details can be obtained on an as-needed basis in the future. At the same time, detailed facts are important for those who will be working in the domain. As mentioned in Chapter 3, content knowledge about a domain is a *major determinant* of problem-solving performance in that domain. In studies of two disparate domains (mathematical vectors and using a video tape recorder), Gordon and Gill (1989) found that subjects' interconnected content knowledge, mapped in conceptual graphs, predicted *85 to 93%* of an individual's ability to solve problems in those domains. Missing concepts or missing links caused problems with performance. These studies and related research indicate that teaching isolated facts is largely useless, while prompting learners to construct a coherent and interconnected set of ideas about a domain is productive and worthwhile.

Langer's seventh point is that many teachers believe there are right and wrong answers. Langer disagrees with this belief, as do most constructivists. Science aims to produce the best model of the world at any given time; it is not necessarily the "right model," the "only possible model," or the "truth." There is awareness among scientists that any theory or observation may change or be replaced in the future, either by generation of new empirical data or by conceptualization of an even more satisfactory and powerful theory. Thinking that we have the "right" model leads to rigidity and fixedness, whereas thinking that what we have is currently the "best" model can lead to flexibility, openness, and continued willingness to question.

A key message that runs throughout Langer's discussions is that students must become motivated to learn (learning can be fun) and that students must take responsibility for their learning. Given its important role in learning, it seems that increasing student motivation to learn should be our number one priority.

MOTIVATION

In studying learning, Rumelhart and Norman (1978) observed that motivation outweighed any cognitive variables they were able to measure. Likewise, Dubin and Taveggia (1969) found that student motivation was a more powerful determinant of learning than any change in teaching strategy. Some steps which are known to increase motivation are:

- giving each student a voice in the class,
- respecting each student's input;
- allowing students to pursue their own questions;
- encouraging students to work in groups and discuss their ideas among themselves;
- creating opportunities for students to create and test their own explanatory models;
- giving students an opportunity to demonstrate their knowledge to others through publication or presentation; and
- providing tools which can sustain student analysis and discussion. *Enhancing student motivation often entails reducing emphasis on learning the facts and increasing emphasis on learning scientific processes.*

MEANINGFUL LEARNING

Ausubel (1968, pp. 37–38), a psychologist who spent his lifetime thinking about learning, describes meaningful learning in this way. The essence of the meaningful learning process is that ideas are related in a substantive (nonverbatim) fashion to what the learner already knows. Each new idea is connected to some existing relevant aspect of an individual's mental structure of knowledge (for example, an image, a meaningful symbol, a concept, or a proposition). Meaningful learning requires two conditions. First, the learner must be motivated to learn in a meaningful way, and second, the material being learned must be inherently meaningful and accessible to the learner. A third condition is that there be sufficient time for meaningful learning to occur, since learning is an effort- and time-demanding process.

Basically, learning involves a number of steps including *perceiving* the world and information in the world, *interpreting* that information, *encoding* it somehow in the mind, *retrieving* it as needed, and then *applying* the information in various contexts. Each of these steps is briefly discussed below.

1) Perception

Our perceptions are limited by our particular perceptual hardware. We cannot "see" like a satellite camera, measuring color or density differentials, nor like an eagle, spotting a small animal on the ground from high in the air, nor like a bee, taking in the ultraviolet spectrum. The world we are able to know directly is constrained and molded by our perceptual hardware.

Since our perceptual limitations filter and define our world, we can never "know" the world absolutely and totally. "Right answers" are elusive. Yet science as a "search for truth" has been a popular conception among science teachers for years. As Langer says, science is often taught as if there is a "right" answer to each question, and the students' job is to memorize those facts or truths about the world.

But this is not how science is actually conducted. Scientists strive to construct the best possible *model* of the world at any given time. They constantly evaluate their models and assess which one is best in terms of its ability to explain, to predict, and to account for many different observations. "Facts" are not necessarily truths but rather well established records of objects or events that are widely accepted to be correct, at least for the time being. In science, a prevailing model can be replaced with another at any time, if the newer model is more powerful and satisfactory. The replacement process can be painful for individual scientists in the "out" group, those who are still attached to the old ideas, especially where large conceptual revolutions are involved (Kuhn, 1970).

Teaching science as if it consists of facts alone is self-defeating, in part because the facts keep changing. Students need to understand that the scientific way of knowing is based upon systematic study of objects and events combined with the construction of models to explain and predict (although prediction is not often possible in the retrospective sciences). Models are tested under a variety of circumstances and by many different scientists. Creation of scientific knowledge is thus a collaborative venture. The public is often confused when they hear conflicting beliefs and claims by different scientists, but such disparate viewpoints are a natural part of a group knowledge-building effort that relies on individual ingenuity, collaboration, and competition. When a particular knowledge claim is challenged, its supporters are prompted to find even more convincing evidence to support their point of view, and so science advances.

A surprisingly effective way for students to learn about the scientific process *and* to develop a fairly deep understanding of science content is to read a good popular book on a subject. In my experience, biology nonmajors who read and discuss *The Beak of the Finch* (Weiner, 1995) while also completing a series of related lessons in