

CONSTRUCTIVISM: A THEORY OF KNOWLEDGE

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INTRODUCTION

Until recently, the accepted model for instruction was based on the hidden assumption that knowledge can be transferred intact from the mind of the teacher to the mind of the learner. Educators therefore focused on getting knowledge into the heads of their students, and educational researchers tried to find better ways of doing this [1]. Unfortunately, all too many of us who teach for a living have uncovered evidence for the following hypothesis.

Teaching and learning are not synonymous; we can teach, and teach well, without having the students learn.

Most cognitive scientists now believe in a constructivist model of knowledge [2] that attempts to answer the primary question of epistemology, "How do we come to know what we know?" This constructivist model can be summarized in a single statement: *Knowledge is constructed in the mind of the learner.*

The goal of this paper is to outline what has been called a "radical" constructivist model of knowledge [3], to describe how this model relates to Piaget's theory of intellectual development, and to outline how this model can help us understand some of the things that happen in chemistry classrooms.

PIAGET'S THEORY OF INTELLECTUAL DEVELOPMENT

In the 15 years since Piaget's model of intellectual development was first brought to the attention of chemists [4], most of the discussion of Piaget's work among chemists has focused on the transition between the concrete operational and formal operational stages [5-13] and ways in which instruction can be revised in light of this model [14-19].

I can remember my first reaction to this model. I was fascinated by its potential for explaining why students had difficulty learning chemistry, and immediately sought a way to test my students, to separate them into concrete and formal classifications. I cannot remember why I wanted to do this, or what I hoped to do with this information, but I can remember being frustrated that no one could provide me with a paper-and-pencil test that could be used in large classes, with high reliability, preferably in 10 minutes or less.

In retrospect, it is obvious that I missed the point. (Some might argue that this is neither the first nor the only time that has happened.) As my colleague has phrased it [7], "Why would chemistry teachers want to identify concrete students at the beginning of the term?" The ability to classify students as concrete or formal is not as important as the realization that there are concrete operational students in our introductory courses, and even more importantly [7], "... everyone reverts to concrete operational or are-operational thought whenever they encounter a new area."

I realize now that discussions of Piaget's work contained words such as assimilation, accommodation, and equilibration/disequilibration that I did not worry about at the time, and I also appreciate the importance of these concepts in fully understanding Piaget's model of intellectual development and the constructivist theory of knowledge which is a logical outgrowth of Piaget's work.

As others have repeatedly noted, Piaget was not a developmental psychologist; he was an epistemologist. He studied the development of thought in children because he believed this was the only practical way of answering the question [20], "How do we acquire knowledge?" Piaget argued that knowledge is constructed as the learner strives to organize his or her experiences in terms of preexisting mental structures or schemes. He also differentiated between physical, logico-mathematical, and social knowledge. The fact that a ball bounces or a glass breaks when dropped on the floor is an example of physical knowledge. Logico-mathematical knowledge consists of relationships between objects, such as comparing the way racquetballs and squash balls bounce. Social knowledge, such as the fact that the racquetball leagues in which I play meet on days called "Monday" and "Wednesday", is based on social conventions.

Piaget also distinguished between *cognitive functions* such as organization and adaptation which remain constant throughout development and *cognitive structures* that change both qualitatively and quantitatively with increasing age and experience. *Adaptation or equilibration* in Piaget's model has been described as an internal self-regulating mechanism that operates through two complementary biological processes: assimilation and accommodation [21].

Assimilation and accommodation can only be understood in the context of Piaget's concept of cognitive structures or "schemes". According to von Glasersfeld, a scheme consists of three parts: a trigger, an action or reaction, and the consequence of this activity [22]. One of von Glasersfeld's examples of a scheme is the sucking reflex in a newborn child. When one touches the child's cheek, it will turn its head, take whatever touched its cheek into its mouth, and begin to suck. The response to the trigger of either the mother's nipple or the child's own thumb is identical, the child begins to suck. From the infant's point of view these triggers are distinguishable, and the thumb is therefore assimilated as an object of the sucking activity or scheme. Assimilation involves applying a preexisting scheme or mental structure to interpret sensory data.

The scheme for sucking is activated or triggered by the child's perception of a particular

pattern of sensory signals. This is a remarkable achievement when you consider that the pattern must be isolated from the wealth of irrelevant sensory signals at any moment in time, and no two situations provide exactly the same pattern of signals. Assimilation of the thumb to the sucking reflex requires that the child ignore differences between the visual and tactile signals provided by the mother's nipple and the child's thumb. These differences are ignored either because the child does not perceive any differences in the sensory data, or because the child pays no attention to the differences that are perceived [23].

Although this analogy focuses on a reflex action of newborn infants, assimilation of sensory patterns to preexisting mental structures or schemes is a constant process throughout life. We assimilate the world in the sense that we come to see it in our way. Disequilibrium occurs when we cannot assimilate our experiences into preexisting schemes, when we encounter a problem because we cannot achieve our goals. Equilibrium is restored by modifying these preexisting schemes until the discrepancy is resolved [24].

The process by which existing structures are modified to fit newly assimilated data is called accommodation. Once again using von Glasersfeld's example, the child eventually learns to distinguish between the visual and tactile sensory pattern (mother's nipple) that leads to milk and the sensory pattern (thumb) that does not. Accommodation occurs when the child realizes that the triggered activity does not give the expected result; when the child recognizes that sucking its thumb does not achieve the goal of satisfying hunger. The child may still suck its thumb, but it no longer expects the same result.

THE TRADITIONAL VIEW OF KNOWLEDGE

The traditional view of knowledge is based on the common sense belief that a real world exists regardless of whether we take interest in it or even notice it. This "realist" perspective assumes that we that we come into the world as discoverers who build copies or replicas of reality in our minds.

This perspective leads to an iconic or picture-like notion of knowledge in which our mental structures somehow correspond to or represent reality as if they were direct copies or pictures. That in turn inevitably leads to the question of how well our knowledge corresponds to reality; something is true if and only if it corresponds to an independent, objective reality.

According to the realist perspective, knowledge and truth are questions of correspondence — what is true is what corresponds to reality ... a statement will be judged true if it corresponds to an independently existing reality and false if it does not [25].

As von Glasersfeld described it, the traditional view looks for a *match* between knowledge and reality in much the same way that one might try to match two samples of paint [3, 26, 27]. Knowledge is true when it consists of statements that accurately correspond to or

match what exists in the real world.

Unfortunately, as the skeptics have so often reminded us, it is impossible to judge how well our mental images correspond to reality because the only way we can perceive reality is through these images. Descartes offered one solution to this problem: Trust that God would not have been so malicious as to provide us with deceptive senses. The "idealists" provided another solution when they suggested that nothing exists but the concepts and ideas carried by the human mind.

Luckily, we can escape the skeptics' paradox without resorting to either blind faith or the solipsism that plagues the idealist school of thought. We can do this by shifting our perspective. The traditional view of knowledge views the mind as a "black box"; we can accurately judge what goes in (stimulus) and what comes out (response), but we can only guess about what is happening inside the box. The constructivist view of knowledge views the environment as a "black box"; each of us knows what is going on in our minds; what we can only guess about is the relationship between our mental structures and the real world.

THE CONSTRUCTIVIST MODEL OF KNOWLEDGE

I suggested earlier that the constructivist model can be summarized in the statement: Knowledge is constructed in the mind of the learner. It has been described in somewhat greater detail as follows [3]:

... learners construct understanding. They do not simply mirror and reflect what they are told or what they read. Learners look for meaning and will try to find regularity and order in the events of the world even in the absence of full or complete information.

Anyone who has studied chemistry, or tried to teach it to others, knows that active students learn more than passive students. Chemists should therefore have a natural affinity for a model which replaces a more or less passive recipient of knowledge with an active learner. The problem with constructivism arises when one tries to look at the logical consequences of the assumption that knowledge is constructed in the mind of the learner.

Von Glasersfeld has repeatedly described the construction of knowledge as a search for a *fit* rather than a match with reality [1, 3, 23, 26, 27]. In the constructivist model, knowledge is assumed to fit reality the way a key fits a lock.

It is the difference between the concepts of "fit" and "match" that shows how radically constructivism differs from the traditional view of knowledge. As long as we adhere to the traditional view in which knowledge corresponds to or "matches" reality, two or more individuals with the same knowledge must have similar copies or replicas of reality in their minds. Once we allow knowledge to "fit" reality the way a key fits a lock, we find ourselves

in a very different position because many keys, with different shapes, can open a given lock. Each of us builds our own view of reality by trying to find order in the chaos of signals that impinge on our senses. The only thing that matters is whether the knowledge we construct from this information functions satisfactorily in the context in which it arises.

The constructivist model is an instrumentalist view of knowledge. Knowledge is good if and when it works, if and when it allows us to achieve our goals. A similar view was taken by Osiander, who suggested in the preface to Copernicus' *De revolutionibus*

There is no need for these hypotheses to be true, or even to be at all like the truth; rather, one thing is sufficient for them — that they yield calculations which agree with the observations.

PIAGET AND CONSTRUCTIVISM

Much of the reaction to Piaget's work (both pro and con) has been the result of a natural tendency to assimilate his writings into existing conceptual structures based on the traditional view of knowledge. This is unfortunate, because Piaget was a constructivist. Although a constructivist perspective has been traced back to the writing of Giambattista Vico in 1710, [1, 3], Piaget was the first constructivist in the sense that his view that knowledge was constructed in the mind of the learner was based on research on how children acquire knowledge.

The extent of Piaget's commitment to constructivism is reflected in his description of the period between birth and the acquisition of language [28].

At eighteen months or two years this "sensorimotor assimilation" of the immediate external world affects a miniature Copernican Revolution. At a starting point of this development the neonate grasps everything to himself — or, in more precise terms, to his own body — whereas at the termination of this period, i.e., when language and thought begin, he is for all practical purposes but one element or entity among others in a *universe that he has gradually constructed himself* [ital added], and which hereafter he will experience as external to himself.

Piaget believed that knowledge is acquired as the result of a life-long constructive process in which we try to organize, structure, and restructure our experiences in light of existing schemes of thought, and thereby gradually modify and expand these schemes. Indeed, his definition of knowledge as "invariance under transformations" has no meaning outside of the constructivist perspective. Piaget argued that objects appear "permanent" or "invariant", as the result of the individual's coordination of experiential data and the subsequent projection of these coordinations onto the world that lies beyond our senses.

From the constructivist's point of view, the data we perceive from our senses and the cognitive structures or schemes we use to explain these data both exist within the mind. Von Glasersfeld has argued that assimilation occurs when what we perceive (percepts) is

adjusted to fit the conceptual structures (concepts) we have already assembled [29]. When that does not work, when our experiences do not fit our ideas, "equilibration can occur by adjusting our schemes (concepts) to fit the sensory data we perceive (percepts), and this process is known as accommodation.

Perhaps the best way of demonstrating how perceptions are assimilated into existing cognitive structures or schemes is the example described by von Glasersfeld [29].

Lettvin, Maturana; McCulloch, and Pitts [30] ... established that the frog's visual system ... makes the frog an efficient flycatcher, because it is tuned for small dark "objects" that move in an abrupt fly-like way. In the frog's natural habitat ... every item that possesses the characteristics necessary to trigger the frog's detector in the proper sequence is a fly or bug or other morsel of food for the frog. But if the frog is presented with a black bead, an air-gun pellet; or any other small dark moving item, it will snap it up as though it were a fly. In fact, to the normal frog's visual apparatus, anything that triggers the detectors in the right way, is a fly.

In other words, assimilation does not find recurring patterns of sensory data but imposes patterns by ignoring differences between what is perceived and what is expected, between the visual pattern of a bead or air-gun pellet and the visual pattern of a fly.

HOW CAN KNOWLEDGE BE VIABLE IN THE CONSTRUCTIVIST MODEL?

The constructivist model raises an important question, "If individuals construct their own knowledge, how can groups of people appear to share common knowledge?" The key to answering this question is remembering that knowledge must "fit" reality. Construction is a process in which knowledge is both built and continually tested. Individuals are not free to construct any knowledge, their knowledge must be viable, it must "work". Von Glasersfeld has argued repeatedly that our experiences test the viability of our knowledge in much the same way that Darwin's theory of evolution tests the viability of an organism [1, 3, 22, 26, 27, 31].

Darwin's theory of evolution is based on the principle of constraints, not cause and effect [32]. Natural selection eliminates organisms that do not fit by operating on a single criterion: Either the organism fits the constraints of its environment or it does not. In much the same way, knowledge is viable as long as it works, as long as it stands up to the constraints of our experiences. The concepts, ideas, theories, and models we construct in our minds are constantly being tested as a result of our experiences, and they survive in a pragmatic or instrumental sense only as long as they are useful.

If you put a group of people, such as potential chemists, through a series of similar academic experiences, expose them to the same shared assumptions about how the world operates, and put them into situations where they test how their knowledge "fits" by talking with other chemists, it is not surprising that when a group of individuals with similar interests gathers at an ACS meeting, an external observer would assume they "share

common knowledge".

The idea that knowledge is viable when it passes the tests of our experience is best illustrated with an example. McDermott has noted that students of different ages and abilities often bring similar misconcepts to the study of physics [33].

... From everyday experience individuals untutored in physics generally assume that a force is always necessary to sustain motion, even at a steady speed. This idea and others that are related serve quite well in daily life.

The knowledge that a force must be applied to keep an object in motion is viable in such commonplace experiences as driving a car; it "works". When faced with the task of making a relatively heavy dry-ice puck move at constant speed across a smooth glass table, it is not surprising that students try to achieve this goal by using a constant blast of air from an air hose [33]. For some students, it is only when they find this does not work that they feel obligated to revise their "knowledge" to incorporate Newton's laws. Once developed, the knowledge contained in Newton's laws is perfectly viable for engineers and even most physicists. It is only when this knowledge is tested in the domain of relativistic effects that it must be altered once more.

EVIDENCE FOR THE CONSTRUCTIVIST MODEL

What evidence do we have that knowledge is constructed in the mind of the learner, and that it "fits" rather than "matches" reality? It is tempting to answer this question by noting that anyone who has ever witnessed an argument between a liberal democrat and a conservative republican should appreciate the fact that individuals not only construct their own knowledge based on preexisting cognitive structures or schemes, but in fact also seem to construct very different worlds in which to live.

A more appropriate answer might cite the results of Piaget's research that led to the constructivist model, but that would take far too much space. I have therefore tried to select individual experiments that might lend support to key elements of the constructivist model.

Regardless of whether knowledge is constructed in the mind of the learner or corresponds to an iconic image or picture of the real world, it must be based on our perceptions of reality. Faced with the question of how accurately our senses depict reality, Descartes suggested trusting in a benevolent God who would not provide us with deceptive senses. There is good reason, however, to question the reliability of our senses. Von Foerster described an experiment in which the word *cogitate* was played back repeatedly at high volume [34]. At first, the word was clearly perceived. But after 50 to 150 repetitions, the subjects abruptly reported hearing another clearly perceived word or phrase. After 10 to 30 more repetitions, another sudden switch occurred. Over 750 different words or phrases were reported, including: agitate, annotate, arbitrate, artistry, back and forth, brevity, can't you see, Cape Cod you say, card estate, catch a tape, computate, conscious state, and

got a date.

Von Foerster also described evidence that suggests that we do not perceive sensory information unless or until we learn to coordinate this information into a cognitive structure or scheme. In one experiment, microelectrodes were inserted into a cat's brain, and the cat was placed in a cage that contained a food box whose lid could be opened by pressing a lever only when a short tone of 1000 Hz was repeatedly presented. In other words, the cat had to learn that a 1000-Hz tone means food. There was no evidence from the microelectrodes that the tone was perceived as long as it was not interpretable. Eventually, however, the cat learned to associate the tone with food, and from that point on, the microelectrodes showed significant mental activity as soon as the tone became audible.

Von Foerster also noted that a successful therapy for individuals with serious brain injuries resulting in loss of a significant portion of their visual field involves blindfolding the patient until the patient learns to attend to the clues concerning posture that come from proprioceptive sensors in the muscles and joints instead of the missing visual clues.

Evidence that we construct knowledge on the basis of preexisting mental structures or schemes was reported by Rosenhan who did an experiment in which eight "sane" people gained admission to psychiatric hospitals by describing symptoms that had never been reported in the psychiatric literature [35, 36]. Once admitted, these pseudopatients ceased simulating any symptoms of abnormality and reported events in their life histories exactly as they had happened. As Rosenhan noted, the stress associated with hospitalization was considerable, and all but one of the pseudopatients wanted to be discharged immediately. They were therefore motivated to behave sanely and to be "paragons of cooperation".

In all but one case, the pseudopatients were admitted to the hospital with a diagnosis of schizophrenia and eventually were discharged with a diagnosis of schizophrenia "in remission". (The patient had to be in remission in order to be discharged, but they had to be schizophrenic or they would not have been admitted in the first place.) None of the pseudopatients was detected by the hospital staff, although it was quite common for their fellow patients to detect the pseudopatients' sanity and voice such opinions as, "You're not crazy. You're a journalist, or a professor. You're checking up on the hospital."

As far as the experimenters were able to determine, diagnoses were not affected by the healthy circumstances reported in the patients' case histories. What happened instead was an apparently unintentional distortion of the facts of the case histories until they were consistent with popular models of schizophrenia.

ROLE OF MISCONCEPTS IN LEARNING

The constructivist model helps explain why students bring misconcepts to chemistry, physics, and mathematics classes and why these misconcepts are so remarkably resistant to instruction. Let's start by distinguishing between "preconceptions" and

"misconceptions".

A "preconception" is a concept or idea which a student has upon entering ... a course, and which has some consequence on the person's work We shall use the term "misconception" for concepts or ideas which from the point of view of the average professional ... lead to unacceptable solutions or answers to questions or problems in the context of a course [37].

What kinds of misconcepts do students bring to science and mathematics classes? Champagne et al. found that student's knowledge of the motion of objects is closely linked to the impetus model proposed by Aristotle; objects in motion have a given amount of impetus that is used up as the object moves [38]. Osborne and Cosgrove found that the vast majority of secondary school students believe that the bubbles in boiling water are made up of either "heat", "air", or "oxygen or hydrogen" [39]. They also found that many children believe that nothing remains when gas is burned; "nothing is left but the taste" when sugar dissolves in hot water; "just the smell" travels to the back of the room when camphor is heated on the lecture table; and nails loose weight when they rust [40].

The misconcepts students bring to science and mathematics classes are remarkably resistant to instruction. Kaput and Clement, for example, originally found that 25-30% of freshmen engineering students had difficulty translating the following sentence into an equation: "There are six times as many students as professors at this university" [41]. The most common wrong answer was " $6S = P$ ". Rosnick found that 22% of a group of students who had successfully completed a year of calculus still chose the "absurd" answer that S stands for professor when asked the following question

At this university, there are six times as many student,,; as professors. This fact is represented by the equation $S = 6P$. What does the letter S stand for?

Lockhead found that about a third of the college faculty and half of the high school teachers given the same task made similar errors [43].

Where do these misconcepts come from? The confusion between the equations " $6S = P$ " and " $S = 6P$ " results from experiences students face in their science and mathematics classes. The equal sign is used in equations to indicate that a calculation should be done. For example, " $S = 6P$ " can be read as indicating that we multiply the number of professors by six to find the number of students. The equal sign is also used, however, in equalities such as, " $1 \text{ ft} = 12 \text{ in.}$ ". If we write the original relationship between students and professors as an equality, instead of an equation, then one professor corresponds to six students, and therefore, " $1 P = 6 S$ ".

Why are misconcepts so resistant to instruction? Each of us constructs knowledge that "fits" our experiences. Once we have constructed this knowledge, simply being told that we are wrong is not enough to make us change our (mis)concepts. The resistance of misconcepts to instruction brings to mind Kuhn's argument that one cannot prove a theory

wrong by experiment, the proponents of the theory will simply make ad hoc modifications to explain the new experimental results [44]. The only way to get rid of an old theory is by constructing a new theory that does a better job at explaining the experimental evidence or finds a more appropriate set of experimental facts to explain. The only way to replace a misconception is by constructing a new concept that more appropriately explains our experiences.

Much of what we do in introductory courses generates misconcepts that are resistant to subsequent instruction. Let me give just one of a limitless number of examples. On a recent hour exam, we asked students to calculate the N-O bond order in the NO_3^- ion. The answer key read: 1 1/3. One of our graduate students was furious, arguing that the only possible values for bond order are integers (0, 1, 2, 3) or half integers (1.5, 2.5, etc.) because "everyone knows" that the bond order is equal to the difference between the number of electrons in bonding and antibonding molecular orbitals divided by two. No amount of argument, from any source, would convince this student that his model was naive, that it was developed from discussions of diatomic molecules, and that it does not always hold for polyatomic molecules.

IMPLICATIONS OF THE CONSTRUCTIVIST MODEL FOR TEACHING

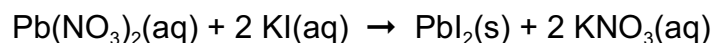
The constructivist model of knowledge has important implications for instruction. Social knowledge such as the days of the week or the symbols for the elements can be taught by direct instruction. It can even be argued that this is the only way that children can learn social conventions [20]. But physical and logico-mathematical knowledge cannot be transferred intact from the mind of the teacher to the mind of learner. The constructivist model therefore requires a subtle shift in perspective for the individual who stands in front of the classroom. A shift from someone who "teaches" to someone who tries to facilitate learning; a shift from teaching by imposition to teaching by negotiation.

As Herron has stated it [45],

The major influence that research in psychology and education has had on my teaching is the portion of the time I spend telling students what I think versus the portion I spend asking them what they think.

He then went on to give an example of how he interprets the statement: Active students learn more than passive students [45].

Even in large lecture sections, I ask my students to generate what they consider to be a sensible solution to problems I may, for example, mix a solution of $\text{Pb}(\text{NO}_3)_2$ and a solution of KI and have students calculate the numbers of moles of PbI_2 that could form ... based on the equation,



I then ... call attention to the fact that the information used in the calculations was the amount of the solid reactant, but the demonstration used the reactant mixed with water I then ask them, "How can I describe these solutions?" . Students make suggestions and I encourage others to evaluate them. We consider things like weight percent and realize that such a description would work, but it would require us to weigh the solution rather than measure its volume, which is a simpler procedure. This often leads to the suggestion that we describe the mass of solute in each milliliter (or liter) of solution, and that is accepted as another suitable description but one that requires a subsequent conversion to moles of solute Eventually, a description in terms of the moles of solute dissolved in each milliliter (or liter) of solution is accepted ..., and a formal definition of molarity is then presented.

There are several advantages to this dialog between students and teacher [45]. It starts with a concept that makes sense to the students, builds from their understanding towards ours, shows why chemists use molarity instead of other approaches that might seem preferable to the students, shows that "chemical knowledge is a product of rational thought" instead of "arbitrary rules to be accepted on the basis of authority", and produces a concept that is "more likely to be meaningful to the students".

The constructivist model also emphasizes the importance of a two-directional flow of information between teachers and their students. At a recent seminar on the systems architecture of AT&T computers, several of us noted that no one mentioned the word "telephone". When this was brought to the speakers' attention after the session, they laughingly answered that the telephone is now a "voice terminal". When asked, "What do you call the 'jack' that phones plug into?", they answered, "An information output device." The problem with the traditional view of knowledge is that teachers tend to focus almost exclusively on their information output devices and neglect the development of information input devices. As Confrey and Upchurch have noted [46], ". . . one of the things that happens as students learn to relate to teachers is that they come close and teachers fill in the blanks."

An example of what happens when a teacher listens to students can be found in the dialog between a teacher and student in Herron's article from the State of the Art Symposium on Chemical Education [45]. This dialog shows many of the signs of a constructivist teacher who questions students' answers *whether they are right or wrong*, insists that students explain their answers, focuses the students' attention on the language they are using, does not allow the students to use words or equations without explaining them, and encourages the student to reflect on his or her knowledge, which is an essential part of the learning process.

The idea that knowledge is constructed in the mind of the learner on the basis of preexisting cognitive structures or schemes provides a theoretical basis for Ausubel's distinction between *meaningful* and *rote learning* [47].

To learn meaningfully, individuals must choose to relate new knowledge to relevant concepts and propositions they already know. In rote learning ... new knowledge may be acquired simply by verbatim memorization and arbitrarily incorporated into a person's knowledge structure without interacting with what is already there [48].

Or as Ausubel has stated [47],

If I had to reduce all of educational psychology to just one principle I would say this: The most important single factor influencing learning is what the learner already knows.

The constructivist model also explains why the logical order for presentation of material in the mind of an expert is not always the best order of presentation so that a novice will learn the material for the first time [49]. The classical sequence of topics in introductory chemistry courses is perfectly logical to someone who has already constructed this knowledge. It builds inexorably towards the point where the students are armed with the tools necessary to understand chemical reactions. Yet there is abundant evidence to suggest that it fails with some (if not many) students. Why does it fail? Perhaps because we tend to forget one of the basic principles of instruction: Students never know where you are going to be in a few weeks (or months); they have a hard enough time remembering where you have been. The constructivists argue that disequilibrium plays an important role in learning. Students need to know that a problem exists before they are willing to accept an explanation.

SCIENCE AS A CONSTRUCTIVIST ACTIVITY

At a recent seminar at Purdue, the speaker defined problem solving as "what you do when you don't know what to do" [50]. He also suggested that the first few steps in problem solving might consist of the following.

Step 1: Try something.

Step 2: Try something else.

Step 3: Look at where the first two steps have taken you.

One member of the audience objected to this model because, in his opinion, it asked students to take the same approach to problem solving that scientists take to doing research. Others argued that the strength of the model was the fact that it assumes some overlap between the techniques students use to solve problems and the techniques scientists use when doing basic research.

There is a great deal of similarity between the constructivist model of knowledge and Kuhn's analysis of science [44, 51]. Others have noted that science is a constructivist activity. Kuhn, for example, has stated [51]:

Science is not just a collection of laws, a catalog of unrelated facts. It is a creation of the human mind, with its freely invented ideas and concepts. The only justification for our mental structures is whether and in what way our theories form a link with the world of sense impression.

Einstein commented that, "It is the theory that determines what we can observe", and Heisenberg noted that "We have to remember that what we observe is not nature in itself, but nature exposed to our method of questioning" [52].

Each individual, student or a scientist, builds his or her own model of the universe on the basis of preexisting cognitive structures or schemes. Progress in science results from the fact that conflicts between theories are resolved by groups of scientists, not individuals. When faced with a choice between theories, Kuhn recommends [51],

... take a group of the ablest available people with the most appropriate motivation; train them in some science and in the specialties relevant to the choice at hand; imbue them with the value system, the ideology current in their discipline . . . ; and, finally, let them make the choice. If that technique does not account for scientific development as we know it, then no other will.

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