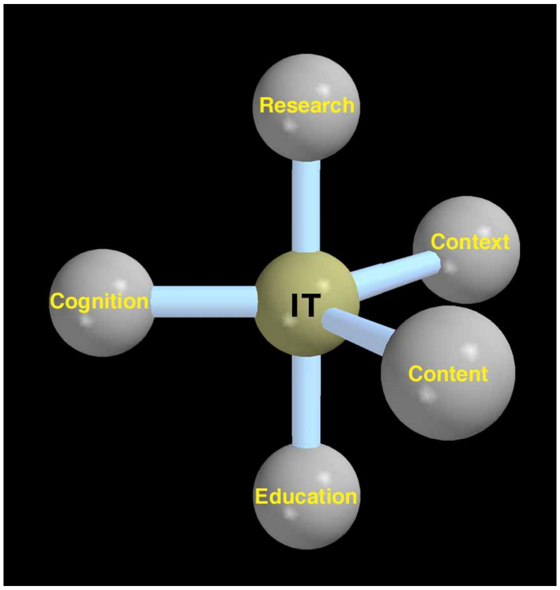

A learned molecule: Information technologies (IT) as a “central atom for the central science” for the integration of research and education through the three pillars of content, context, and cognition.

Thinking About Education in Chemistry Courses and the Integration of Research and Education for Undergraduates: Informed, Enabled, and Enhanced by Information Technology (IT)

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Dedicated to the memory of George Pimentel and all great teachers. "He came to the ball park everyday, and he always came to play hard."

Food for thought: thinking about thinking. Content, context, and cognition as three pillars of an intellectual model for teaching and learning and for integrating research and education.

> *"We teach what we like to learn and the reason many people go into teaching is vicariously to re-experience the primary joy experienced the first time they learned something they loved."*—Stephen Brookfield

Learning the process of critical thinking is an important goal of a good education in chemistry or any other science or engineering course. However, I don't recall participating in many discussions with my research colleagues about exactly what cognitive processes are involved in learning how to think critically, or about how we might connect such processes to teaching and learning. I also don't recall discussing or reading how the form of critical thinking that we seek in educating students compares to the form we seek in performing research. This essay is my attempt to provoke a discussion of thinking about thinking, and then to apply the results of such discussions to improving teaching, learning, and research in chemistry at all levels.

My central task here is to explore the creation of an intellectual model for effective teaching (education) and mentoring (research) and therefore to investigate models for integrating research and education. I will first review my recollections of how I developed my current personal model of thinking about thinking—employing appropriate license to provide a storyline with a bit more coherence that it probably had in reality. Next, I will review how I employed this model to integrate information technologies into my teaching and research programs. Finally, in a separate historical piece (see J. *Chem. Educ.* **2005,** *82*, 1292-1301.) I have described how my colleagues and I applied the model to the use of information technology (IT) in our education and research programs. It is important to state at the outset that IT can assist in effective teaching and learning only if it employs the principles of a robust intellectual model for cognition.

The buzzword "meta-cognition" refers to an explicit attempt to keep track of the intellectual processes that occur during the process of learning. To cover all these processes I'll use the simple term *cognition*: a process or collection of processes by which one actively tries to control the effectiveness of acquisition of new knowledge, whether at the novice level (e.g., when undergraduates learn content) or the apprentice level (e.g., when graduate students learn the methods of inquiry and discovery) or the expert level (e.g., when a faculty member analyzes data from a sophisticated experiment). In short, cognition refers to the process of *deliberate and systematic thinking about thinking***.**

My attempt to understand how my own cognitive processes is still a work in progress (I'm still thinking about it), but has brought me to a model that attempts to integrate teaching, learning, and research seamlessly as involving the same intellectual processes within a single consistent structure. In an attempt to generalize the cognitive process, I have sought the minimum number of components that would be essential for application to activities integrating education (operationally defined as the teaching/learning relationship) and research (the mentoring/learning relationship). I propose that an education and research model that connects and integrates the following three essential components or pillars can be broadly applicable and successful: *content, context,* and *cognition* (see Table 1). Of the three, context and cognition are completely independent of content and therefore are completely independent of discipline. Thus, the real task is to understand the roles of context and cognition in the education and research relationships, then apply the relationships effectively to any content, i.e., any activity in the sciences or the humanities.

Table 1. The "three pillar" (content/context/cognition) model for education and research.

Content (knowing what, where, or when) can be roughly described in my model as the information or knowledge that is of interest for teaching or research in any discipline. Content is exemplified by the material in textbooks. For this essay, the content is the information and knowledge contained in the discipline of chemistry. Content is easy to find, is agreed on by the community of chemists, and is available for all to use.
Context (knowing how) can be roughly described in my model as the driving forces that provide motivation making the content of interest to the individual. For students of chemistry, the context for learning can vary widely—from a passionate and inherent interest in the content of chemistry to a total lack of interest in the subject but the desire to get a cursed requirement out of the way. For researchers in chemistry, the contexts for learning are more tightly focused and are more usually associated with a desire to obtain a scientifically deep, penetrating and gratifying understanding of the content.
Cognition (knowing why) can be roughly defined in my model as the intellectual process of developing structures and causal relationships that will be useful in any learning situation, either education or research. If properly developed, cognition provides the intellectual structure for the most effective execution of learning and inquiry that are at the heart of education and research. I will propose that qualitative and quantitative forms of geometry are very effective devices for developing efficient cognitive structures.

I propose that the development of teaching and research skills require the proper interplay of these three principles in order to achieve the highest degree of effective student learning and scientific inquiry.

Intellectual connections between observations and intelligence. Cognitive survival skills.

"An important difference between genius and ignorance is that genius has its limits."—Albert Einstein (with apologies)

Consider the following process of cognitive evolution:

observations→ data → information → knowledge → intelligence → wisdom.

These terms, progressing from left to right, imply an increasing level of intellectual development and a higher order of cognitive structure. I view this evolution as being correlated with an increasing level of *cognitive survival skills*, using the term "survival" deliberately here: I wish to evoke an image and analogy of the Darwinian notion of how organisms struggle to adapt to their physical environment and develop biologically relevant survival skills. We shall have more to say about this metaphor later, but for now let's just see how the concepts of content, context, and cognition serve as intellectual vehicles that can take an individual from observations to intelligence.

Observations refer to direct cognitive interactions of an individual with his or her environment. Chemical observations refer to the cognitive interactions of an undergraduate student or researcher within the controlled environment of a laboratory setting. Observations are converted to data in a form broadly agreed upon by a discipline's practitioners and based on a discipline's paradigms. The raw data may carry little meaning to the undergraduate student or novice researcher unless they are formatted in a structure that transforms them into *information,* a higher cognitive structure. *Knowledge* implies that the individual knows how to use information to act on the environment. *Intelligence* implies that he or she has achieved the ability to apply information on the environment in an effective way and thereby to hone survival skills. *Wisdom* is the uncommon intellectual ability to apply a combination of intelligence and good judgment to a global set of actions on the environment.

How does chemistry fit into all this philosophical stuff? The discipline of modern chemistry uses *molecular structure* as the universal intellectual tool to transform data into chemical information that we can call the content of chemistry. A student can be familiar with the information of chemistry without having knowledge of chemistry, i.e., having chemical information alone does not provide the ability to act on the environment. I now try to provide some insight to what I mean by context: context is intellectual setting or circumstances in which the individual employs information (e.g., content in the textbook) and transforms it into knowledge (e.g., cognition that allows action on the environment). The combination of content, context, and cognition provide a powerful intellectual matrix for producing an understanding of chemistry. Experience creates judgment, which can eventually transform intelligence into *wisdom*.

Let's now expand a bit on some historical background that should show how I developed the above model and perhaps provide the model with some level of plausibility and credibility.

In the beginning….

"Many journeys begin looking at the dim light at the end of a tunnel. Hopefully the end of the journey is not a light-year away." —Anonymous

My journey of self-reflection on teaching and learning probably had its beginning with discussion that I had with Professor Gilbert Burford, one of my great undergraduate teachers and role models, during my undergraduate years at Wesleyan University. During my exit interview as a senior, Professor Burford asked me what I thought it takes to be a good teacher. After a little reflection, my answer was something like "A good teacher can remember the difficulty and intellectual struggle that are involved in learning a new subject and can keep track of the cognitive tricks that build on things the student already understands in order to facilitate the comprehension of new knowledge. In this way, the teacher can retrace the path of thinking that was effective for him or her and hope that it will help students to learn." Although I didn't know it at the time, I was evidently thinking like a constructivist.

During my years as a graduate student at Caltech from 1960 to 1963, with George Hammond as a mentor, I had a NSF Fellowship, which allowed me to devote full time to research. In the laboratory, I experienced the novice researcher's fluctuating mix of frustrations and exhilaration, a cognitive vertigo that comes as part and parcel of learning a new subject.—in this case a subject, organic photochemistry, that at that time was an emerging discipline and had not yet developed a mature paradigm. With George's outstanding mentoring I learned firsthand the process of creating a paradigm in an evolving field of science. As a novice, this process involved continually reconstructing my limited prior knowledge. Through discussions with George, other students, and other faculty (or just about anyone I could corral) about photochemistry and spectroscopy, I was able to develop for myself and learn a paradigm of organic photochemistry that not only made sense to me but that I could employ to teach others.

During my year as a postdoc working with Paul Bartlett at Harvard I was able to test the effectiveness of the paradigm of organic photochemistry that I had developed under George Hammond's mentoring. Paul invited me to pinch-hit for him and deliver a lecture on organic photochemistry to his undergraduates in his course on physical organic chemistry. I put together some notes, reconstructing as best I could the path that I had used to teach myself a paradigm of organic photochemistry. I was astonished and delighted to receive a standing ovation by the class at the conclusion of the lecture! This was a good feeling and sold me on the idea that I was doing something right with respect to the instructor/student interface. Evidently word got around that I could teach photochemistry pretty well, and I was later invited to present a series of lectures on organic photochemistry to the chemistry faculty at Harvard. At that time the senior organic faculty consisted of Paul Bartlett, Robert Woodward, Frank Westheimer, and E. J. Corey. Roald Hoffmann was also there as a junior fellow who had just started to perform computational photochemistry and to work with Woodward on the theoretical basis for what became known as the Woodward-Hoffmann rules. The idea of teaching something to this group was pretty heady stuff, and looking back it was a pretty gutsy thing to do. But the lectures and associated discussions went very well. By this time I was beginning to build up a profile of notes on photochemistry that incorporated my paths to understanding and the creation of a paradigm that I figured would be the makings of a course on organic photochemistry someday.

Then serendipity did its thing. I received an opportunity to develop a course on organic photochemistry much faster than I expected during my tenure as a postdoc at Harvard. My Ph.D. supervisor, George Hammond, had received an offer to teach a course on organic photochemistry at DuPont in Wilmington, Delaware. He was unable to accept but recommended that DuPont invite me to teach the course. I was invited and accepted. I dug into my notes and decided to use the occasion of the course to penetrate deeply into all kinds of issues, which required me to create a detailed and expansive paradigm of organic photochemistry that would allow me to show the researchers at DuPont my path to understanding. The course was a wonderful experience, and the notes and suggestions and feedback from the students were used during my first year at Columbia as a basis for a textbook on organic photochemistry, *Molecular Photochemistry*[1].

It was about this time that I began to reflect seriously on what I was doing in my teaching style that seemed to make it effective. My hope was that I could discover a formula for cognitive processing that would work not only for my teaching but also for my research program at Columbia University, and thereby assist me in obtaining tenure. Could the two programs of education and research be, so to speak, imaged one upon the other? If so, a path for the integration of education and research seemed to be a natural corollary.

The importance of context in learning. From Darwin's theory of biological evolution, a survival-skill-driven theory of the cognitive evolution of a mind.

> *"I have called this principle, by which each slight variation, if useful, is preserved, by the term of Natural Selection."* Charles Darwin

From the outset it seemed to me that the exhilaration that I experienced when learning a new subject or teaching students to learn or making a new discovery in the laboratory was akin to the development of a survival skill as described by Darwin's theory of natural selection. I therefore sought to explore the possible cognitive connections between natural selection and education/research.

From high school biology my understanding of the basic concept of natural selection is that environmental conditions (or "the physical world") determine (or "select") how well particular traits of organisms can serve for the survival and reproduction of an organism[2]. The evolution of the biological traits of an organism (natural selection) involves the process of biological change and adaptation in response to a changing physical environment. By analogy, the evolution of the intellectual traits (education or research) of an individual mind involves the process of creating new knowledge in response to a changing physical or intellectual environment that produces new information.

Thus, an "evolutionary" explanation of cognitive development is that knowledge allows an individual to adapt to any new environments by allowing an understanding of experiences and by providing an increase in the individual's fitness to survive and to become more attractive as a possessor of valuable *intellectual genetic* material. The basic idea is simple, even naïve: nature, through evolution, makes us feel good when we develop any physical skills that allow us to act on our environment. By analogy, we feel an exhilaration when we develop new intellectual skills that allow us to interact more effectively with our environment. An organism is comfortable or “at cognitive equilibrium” in an environment to which it is adapted, but survival pressure serves as a driving force for the organism to feel uncomfortable or in cognitive disequilibrium in a new environment. This mechanism provides a motivation to develop new survival skills in order to survive in the new environment. Our model suggests that organisms are driven to adapt their knowledge in order to obtain a balance between the expectation produced by their intellectual processing and the results of their experiences in acting on their environment. I use the term *intellectual closure* to describe the goal of the knowledge construction process that produces cognitive equilibrium. With closure comes the comfortable and gratifying feeling that one has adapted to the environment.

We can also push the analogy between biological and intellectual evolution further to conclude that the act of effective teaching is akin to the passing of intellectual genetic materials from the teacher to the student (or from mentor to novice researcher). As teachers we experience an exhilaration when we have evidence that we have taught effectively. Students experience exhilaration when they have evidence that they have learned effectively, because they feel they have improved their intellectual genetic materials, which will allow an enhancement of their survival skills. This idea explains the exhilaration that an undergraduate feels when a new idea “clicks,” or that a graduate student experiences when an experiment meets expectation or provides insight and merits a major or minor “Eureka!” (pardon my Greek). The drive for physical fitness of the organism is analogous to the quest for intellectual fitness of the mind.

To shift our focus from the immediate individual experience to the transformations taking place on larger social and chronological scales, learning is most effective when it is accomplished in a context that gives meaning to the content. The context in which learning occurs is the driver, related to survival skills, that motivates the student to want to learn and to feel exhilaration when the learning is effective. The Darwinian view leads to the idea that learning works best when it is reinforced by experience, i.e., by demonstrating that certain cognitive actions lead to reproducible results with respect to answers (homework, class discussions, quizzes, exams) or research results (reproducibility of techniques). Discussions with peers can provide another useful context that validates the learning. Once the student understands how the content is related to his or her interests (job opportunities, certification for future courses, etc.), this context promotes engagement in the learning process.

An instructor has the important function of providing meaning to isolated facts, making connections across disciplines, and placing content in a larger, engaging context**.** This requires serious, disciplined scholarship and an understanding of how to bring new insights to the student.

Lessons on cognition from Piaget's studies of the intellectual development of children.

"The human mind treats a new idea the way the body treats a new protein; it rejects it."
—P. B. Medawar

My interests in using information technologies (IT) for educational purposes and for research purposes arose about the same time. This is natural, since the wide appearance of computers in the early 1980s triggered potential revolutions in information exchange and communication. For me, the arrival of the computer as a force in education and research coincided with my growing interest in how students think. The latter was in turn triggered by my discussion with my daughter Cindy about her college courses in human development, especially material dealing with the intellectual development of children. These conversations brought up the work of Jean Piaget,[3] which I found fascinating. Piaget's model of how children learn resonated with my experience with my own children, so I took it seriously.

Piaget proposed that the learning process involves constructing knowledge in an intellectual structure that he termed a *schema*. When learning is consistent with the schema, the individual feels a level of comfort because the intellectual system is in a state of equilibrium. Piaget used the term *assimilation* to describe knowledge that is accumulated, is consistent with the preexisting schema, and reinforces the feeling of mental equilibrium. However, when certain ideas are learned, they may cause cognitive disequilibria, because they cannot be assimilated into the intellectual structures of the schema. This uncomfortable feeling creates a tension that is a driving force for resolution. When schemata are modified in an acceptable way, cognitive equilibrium returns. Piaget termed the process of changing schemata in reaction to a changing environment *accommodation*. Thus, the learning process consisted of (1) assimilation of knowledge that is consistent with the individual's existing schema and (2) accommodation from time to time of new knowledge that is incompatible with previously existing schemata. Each new intellectual equilibrium brings the mind to a higher, more adaptive level and to a higher level of learning.

Figure 1 translates Piaget's ideas into a concept map for education. The usual everyday learning from interactions with the environment or from being in the classroom consists of assimilating knowledge by a cyclic process of generating puzzles and solving them using preexisting knowledge. However, when the puzzle cannot, despite the student's best efforts, be solved with preexisting knowledge, the requirement for the accommodation of new knowledge results. In the content of the student in undergraduate courses, this can result in a crisis when an exam is imminent. If the learning is good and the new knowledge has been properly accommodated, the student will *nail* the exam. When the learning is poor and the new knowledge has not been properly accommodated, the student will *fail* the exam.

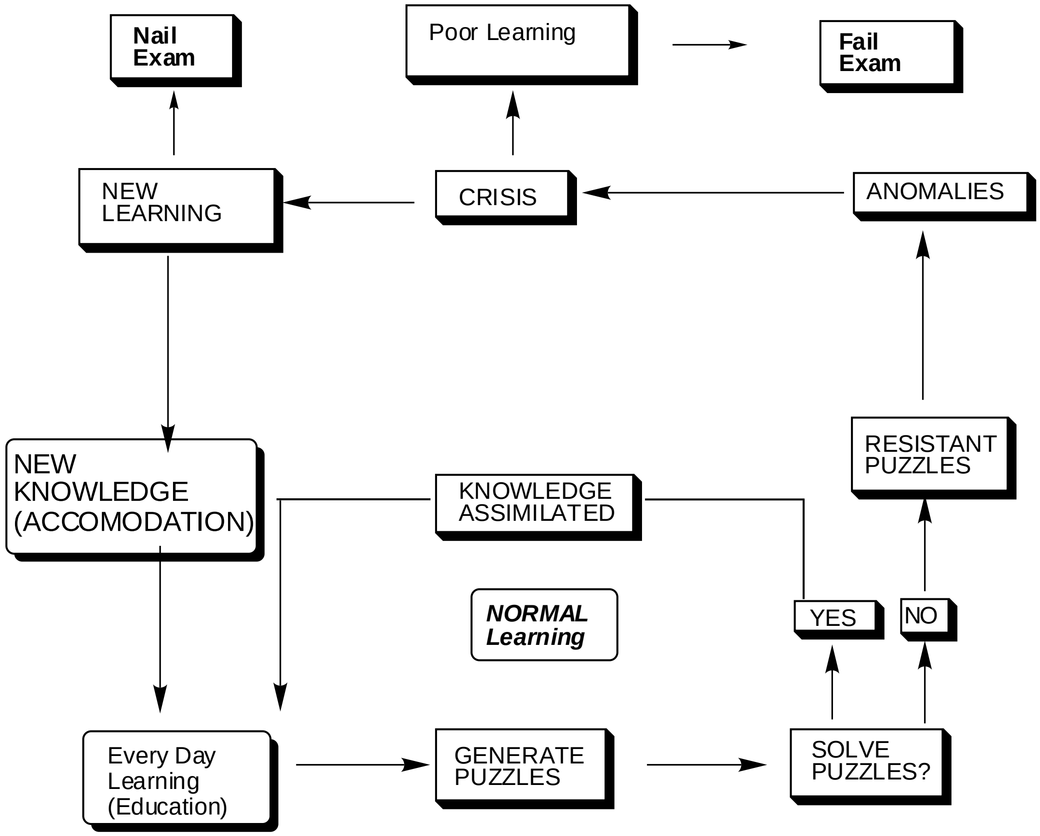

Figure 1. A concept map of the process of everyday knowledge construction (Piaget s assimilation of education) and of extraordinary knowledge construction (Piaget s accommodation).

According to Piaget, intelligence consists of possessing knowledge and intellectual tools that allow the individual to *act* effectively on the environment. This idea connected nicely with my Darwinian model of intellectual development and the importance of context in learning. Piaget also proposed that children proceed through various stages of intellectual development, the two most relevant to education being the *concrete operational* and *formal operational* stages. I found that this concept resonates strongly with my experience teaching undergraduate students. The concrete operational level of cognitive development (according to Piaget, typically achieved by children between the ages of 7-12) is characterized by the ability to reason logically, organize thoughts coherently, and think about concrete physical objects that exist in the present. However, at this intellectual level a child has not yet mastered abstract thinking, logical reasoning, handling hypothetical situations, and comprehending time dependencies. Abstractions, such as imagining the steps and timing in a mechanism of a chemical reaction for which only the reactants and products are given, are difficult for a student at the concrete operational level of intellectual development to handle. For such students, the possible is represented by the objects in the present environment and by concrete representations of that environment. At this cognitive level the environment consists of space, objects occupying space, time, motion of objects in space (dynamics), conservation laws, and causal laws in the present. These students cannot handle multiple hypotheses and multiple rules effectively and can apply rules only one at a time. When they encounter multiple rules that appear contradictory, they cannot process them at the same time, and they apply a single rule to all cases. The student at the concrete operational level assimilates knowledge consistent with preexisting knowledge but has difficulty in accommodating knowledge that generates conflict.

At the highest level of cognitive development, the formal operational stage (typically starting in the teens, according to Piaget), children can solve abstract and hypothetical problems that are time dependent. Students now become capable of thinking more like scientists: they devise strategies for solving problems logically and with internal consistency, and they assign causal relationships to time-dependent phenomena. They can readily accept the notions of testing a problem systematically and weighting evidence to favor or disfavor *multiple hypotheses*. Cognition is no longer tied to events or objects that are observable in the immediate present. Hypothetical situations are acceptable and accommodated as part of the cognitive process.

An important point for undergraduate education is that there is some evidence that about 50 percent of the students in college may not reach the formal operational stage of cognitive development. This possibility should be a critical concern and taken into account by teachers of chemistry, since our science is based on an invisible microscopic world that cannot be seen directly, but must be hypothesized and investigated by indirect means.

A model for the cognitive relationships of research and education. From Piaget's schemata to Kuhn's paradigms.

> *"There is no use in trying," said Alice; "one can't believe impossible things."*
> *"I dare say you haven't had much practice," said the Queen. "When I was your age, I always did it for half an hour a day. Why, sometimes I've believed as many as six impossible things before breakfast!"*—Lewis Carroll

Piaget proposed that children's intellectual development involves the use of schemata, which organize and structure cognitive processes. These basic intellectual building blocks are connected through patterns derived from experience and then expressed as structures that allow action on, or adaptation to, the environment. But what are these structures, these schemata, that allow the everyday processes of assimilation or the conflict and resolution of accommodation? Do Piaget's ideas, which apply quite transparently to the education of students, extend to the mentoring and training of students involved in chemical research? About this time in my journey I discovered a book that answered one of these questions elegantly and definitively for me and that allowed a preliminary completion of my model. In *The Structure of Scientific Revolutions*, philosopher of science Thomas Kuhn[4] coined the word *paradigm* as a scientific descriptor. His book caused a *paradigm shift* in the way that the process of scientific research is viewed.

Kuhn describes advances in research in a mature science (e.g., physics, chemistry, or biology) as being performed in two phases. In one phase of research, *normal science*, a community of scientists operates under the influence of a constellation of knowledge, theories, techniques, methods, and attitudes that can be termed their paradigm: a sort of *scientific constitution* that this community has agreed to follow. For example, chemists work under a paradigm that assumes that all physical and chemical phenomena can be explained by the ideas implied by the existence of atoms and molecules, along with the implied substructure (nuclei and electrons) and implied suprastructure (supramolecular structure) of molecules. *The acceptance of this paradigm defines the chemical community*. Indeed, the accepted paradigm of the community defines what legitimate entities exist and which legitimate methods should be used for their investigation. Normal everyday research in chemistry is the investigation, within the constitution of the paradigm, of puzzles created by researchers to articulate and expand the paradigm.

In a qualitatively different phase of scientific research, a mature science is faced with real, resistant puzzles that are not solvable within the usual rules of the reigning paradigm. If the solutions of these extraordinary puzzles require a serious and basic modification of the paradigm, which is analogous to a constitution, they constitute an apparent violation of the constitution. When, as the results of revolutionary research, the community becomes convinced that the field requires basic revisions in its working constitution in order to make sense of the new observations, then a paradigm shift, which Kuhn terms a scientific revolution, has occurred. In reading Kuhn's classic text, I detected a connection between the cognitive aspects of teaching and learning (education, Figure 1) and of mentoring and discovery (research, Figure 2).

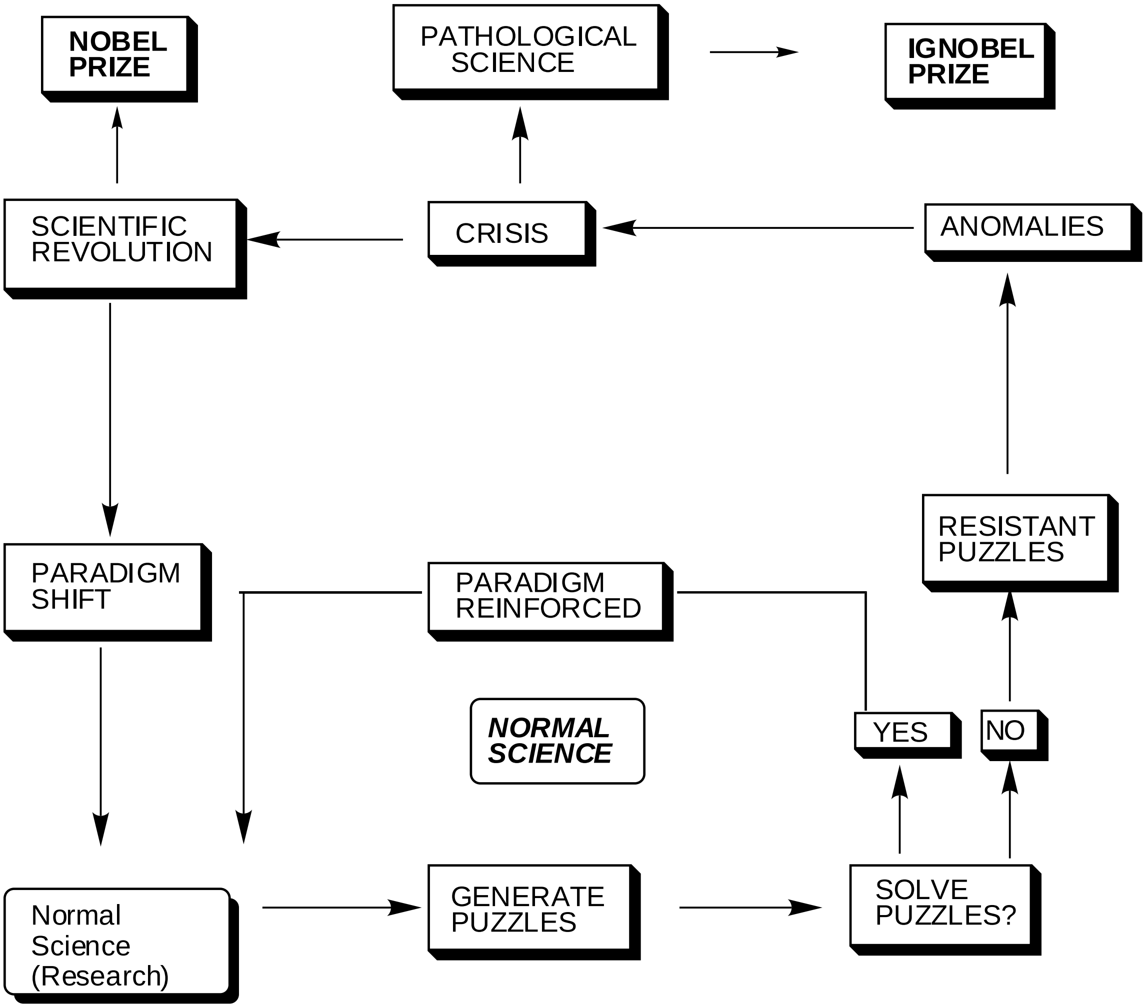

Figure 2. A concept map of the process of everyday scientific inquiry and discovery (Kuhn s normal research operating under the guidance of the paradigm) and of extraordinary scientific inquiry and discovery (Kuhn s paradigm shift).

In summary, according to Kuhn, scientific research is based on a sort of intellectual *"Aufbau* principle" starting with a characteristic set of beliefs (prior paradigmatic knowledge) that the practitioners of a discipline share and implicitly accept as a scientific constitution. A mature science is defined by a paradigm (or set of paradigms), which is characterized by the general acceptance of two elements by the members of the discipline: (1) a broad base of beliefs and (2) a scientific, disciplined, scholarly approach to inquiry, discovery, and creation of new knowledge. However, some new knowledge is not accepted easily, since truly new knowledge implies a required modification or complete replacement of prior knowledge, the stuff of cognitive disequilibria. New knowledge corresponds to a paradigm shift to some degree. Paradigm shifts are cognitively uncomfortable for scientists who seek a way to accommodate a new paradigm within their existing paradigm's framework, just as students strive to accommodate new knowledge within the framework of their existing knowledge. To chemists working in the paradigm, asking them to believe in chemistry outside of the paradigm seems like asking them to believe in "impossible things" of the type that Alice could not imagine.

Integrating the processes of cognition and learning (education) with the process of inquiry and discovery (research).

"Who dares to teach must never cease to learn."—John Cotton Dana

At its best, research is a passionate engagement by a community of scholars with a commitment to discover and create new knowledge for its own sake in a disciplined, systematic, process-driven manner. The process of inquiry and discovery involves continuous discussions with other scientists, the testing of new knowledge in challenging new contexts, and the incorporation of the new knowledge seamlessly in the core intellectual base of the paradigms of science. Mature sciences continuously apply the knowledge of their paradigms to act on new settings. For example, the essence of the paradigm of molecular structure formulated over 150 years ago and its elaboration during the past century is applicable today and does not require any drastic reformulation in its application to new technologies such as nanoscience or molecular biology. However, according to Kuhn, all scientific knowledge is tentative and is embedded in paradigms that are subject to change as the result of new experiments and new ideas. Viable constructs are those accepted by the paradigm, i.e., by social agreement.

Let us explore the analogy between Piaget's theory of education and Kuhn's philosophy of research. Both undergraduate students and novice researchers enter the learning process with preconceived ideas or knowledge, Piaget's "preexisting knowledge" being the schemata and Kuhn's "received beliefs" being the received paradigms. The student is in a state of comfortable psychological equilibrium when new knowledge can be assimilated into current schemata without conflicts. The scientist is also in a comfortable psychological state when new laboratory observations can be assimilated into the currently accepted paradigm without conflicts. Psychological discomfort and disequilibrium occur when a student confronts new knowledge that requires significant and apparently conflicting accommodation with current schemata, or when a scientist is confronted with new knowledge that appears to require a serious paradigm shift. The socially enhancing aspects of a student's learning (peer learning) are matched by the sociological aspects of paradigms determining the research that is performed in a mature scientific field (collaborative and interdisciplinary research). Changing student concepts of normal experience to the concepts and process of science is not easy, because the already existing concepts provide an intellectual filter, so to speak, for assimilating the new content. The same holds for changing paradigms in a scientific field. Trying to convince an expert scientist that an idea appears to exist outside the paradigm has the same intellectual implications as trying to teach a student new ideas that appear to exist outside of his or her existing knowledge.

One of the greatest paradigm shifts in the history of science was the shift from classical physics which required the acceptance of the notion of quantization. Max Planck must have known something about the attitude of scientists to such a revolutionary idea. His following comment[5] is a classic statement of the process by which true paradigms become accepted in science:

> "New scientific truth usually becomes accepted, not because its opponents become convinced, but because opponents gradually *die* and because the rising generations are familiar with the new truth at the outset."

To change a paradigm, a researcher must first understand explicitly that the paradigm exists and directs the thinking of a community of practitioners. Armed with this knowledge, the scientist can then act and attack the paradigm directly and effectively. To change preexisting knowledge, a teacher or student must understand how this knowledge determines the student's thinking, then direct the teaching and learning accordingly. The most important single factor influencing learning is what the learner already knows or believes. A teacher needs to know what the learner knows before he or she can "teach accordingly" and effectively change the learner's knowledge. In research, knowing the paradigm is the key to performing effective normal inquiry. Research outside the paradigm is revolutionary by definition.

Geometry, intellectual processing, and intellectual closure.

"The human mind has first to construct forms, independently, before we can find them in things. How can it be that mathematics, being after all a product of the human intellect independent of experience, is so admirably adapted to the objects of reality?"—Albert Einstein

The cognitive processes of student learning and scientific inquiry are somewhat analogous since accommodations and paradigm shifts involve a change in an intellectual structure. I now needed to come to grips with a more precise and explicit description of this structure so that the cognitive process of education and research could be expressed in a more unequivocal and plausible manner and thereby be more readily applied to a variety of situations. The concept of cognitive structure was developed from two roots: the concept of structure in chemistry, which clearly works very well, and the concept of structure as a form of geometry. Reading René Thom's *Structural Stability and*

Morphogenesis,[6] a book on the mathematics of topological geometry, provided a connection between the cognitive aspects of Piaget's schemata and a formal structural basis for developing schemata.

Why should we employ geometry as a basis for cognitive structure? Perhaps we may find the answer by going back to the fundamental Darwinian basis of cognition and speculating how cognitive development occurred during the brain's evolution. Survival pressure required the brain to develop cognitive tools that would allow constant adaptation to the physical environment, which consists of three-dimensional space, objects occupying space, the motion of these objects in time, conservation laws, and quantities. In Piaget's terms, accommodation requires that the brain acquire and process an enormous amount of information. This is where *topological geometry* comes into the picture. Topological geometry is concerned with the components of a structure and their connections; because this field involves the qualitative aspects of a structure alone, it allows the processing of huge amounts of information. These connectivity relationships are the stuff of *causality*, the ultimate basis of cause-and-effect relationships, which must be mastered to survive in any environment. It seemed to me that the brain, through evolutionary pressure, developed the means of processing the environment in terms of topological geometry in order to handle enormous amounts of information, especially information related to cause and effect, but at a qualitative level. This qualitative state corresponds to an equilibrium or state of comfort. When a challenge from the environment arises, the brain needs to switch from a qualitative to a quantitative view. The later can be viewed as corresponding to Euclidean geometry, for which quantitative metric relationships exist.

I conjectured that geometry is a cognitive tool that developed during evolution in order to resolve the ever-present tension between preexisting knowledge and the reality that results from interaction with the environment. The mind, I propose, has a natural tendency to perform intellectual processing toward as *closed* a mental state as circumstances permit, a sort of Occam's razor for intellectual closure. The origin of such a driving force can be traced to its survival value and the associated evolution of an appropriate genetic composition of the human brain. Intellectual closure involves the goal of achieving a complete, stable, and self-consistent interpretation of the environment. The mind, in order to achieve closure, tends to intellectually complete an unfinished act, to interpret an ambiguous object in terms of its familiar aspects, and to perceive a word, object, or situation in a manner that allows cognitive closure. We have seen in the above discussion that learning involves the resolution of conflicts among preexisting knowledge and experience that is in apparent conflict with that knowledge. *I propose that geometry is a powerful instrument for effecting such closure.*

Let us now put some flesh on these geometric ideas.

Geometry as the underlying structure of cognitive processing: composition, constitutions, configuration, and conformation.

> *"The connectedness of things is what the educator contemplates to the limit of his capacity."*—Mark Van Doren

If the forms of information in the mind were generated from the stimuli provided by the environment in which our ancestors were embedded, the recognition of forms in terms of a three-dimensional geometry has *special* survival value. This value, we postulate, led to the development of perceptual receptors in the brain that are particularly suited to embracing and processing 3D geometric forms to recognize objects in space. A corollary of this postulate is that Euclidian geometry, with its powerful methods for processing geometric structures and its logical, internally consistent mathematical basis, can take on enormous importance as a vehicle for intellectual processing.

Let us now consider how geometry can provide a powerful structural basis for cognitive processing. In mathematics, information can be represented by concrete or abstract forms that are independent of the eventual knowledge into which the information is converted. According to the topological geometrician René Thom,[6] the mind has a natural tendency to assign to forms and shapes of objects observed in space some intrinsic meaning related to the need to enhance survival:

> “..our perceptual organs are genetically developed as to detect objects such as living beings that play a large role, as prey or predators, in our survival and in the maintenance of our psychological equilibrium. It is clear that some forms have special value for us or are biologically important, for example the shapes of foods, of animals, of tools. These forms are genetically imprinted into our understanding of space, and … are narrowly and strictly adapted to them.”

The notion that intellectual processing involves mainly 3D structures in Euclidian space is too restrictive, however. Topological geometry or topology, a much more elastic and flexible branch of geometry, is very important in intellectual processing, especially processing complex amounts of information continuously and rapidly. This branch of mathematics is concerned with the “sameness” of mathematical forms, even when the forms have very different shapes. Topology has been termed *rubber-sheet geometry* to emphasize that topological properties may be visualized as those geometric properties of a Euclidean figure drawn on a rubber sheet that are conserved upon twisting and stretching of the sheet. In particular, the fundamental geometric properties of connectivity, sequence, and continuity of points are preserved even as the appearance or form of the figure drawn on the sheet is distorted by the twisting and stretching. In spite of the distortions, the mind can readily map the process by imagining it in time and recognizing that the many possible shapes are representations of the same object. For example, a square, a circle, a triangle, and the irregular shape made by a rubber band are all of the same form to a topologist, who can readily classify each as a collection of connected points.

An extensive discussion of the comparison of Euclidean and topological geometry can be found in my essay[7] “Geometric and Topological Thinking in Organic Chemistry.” Here, let us only discuss how chemistry uses both topological and Euclidean geometry among its fundamental bases for structuring chemical information. The hierarchy of increasing information content in geometry is given by the ranking: composition, constitution, configuration, and conformation. These are mathematical terms; Table 2 lists their geometric and chemical interpretations.

Table 2. Levels of information content organized by structural representation, in both geometric and chemical senses.

	Geometry	**Chemistry**
Composition	the number and kinds of mathematical elements in a set	the number and kinds of atoms in a molecule
Constitution	the connectivity or neighborhood relationships of the elements in a set	the connectivity of the atoms of a molecule
Configuration	the representation of the elements that are neighbors of a given element in a set by a three-dimensional figure	a 3D representation of the atoms about a central atom
Conformation	the representation of all of the elements of a set by a 3D figure	the representation of a particular shape of a molecule

Finally, the conversion of one structure (reactant molecular structure) to another (product molecular structure) in time is the stuff of chemical change.

When organic chemists deduced the existence of isomers by assuming that molecules could be represented not only by compositions (numbers and kinds of atoms), but by *constitutions* (how the atoms of the composition are connected), and that for a given composition, more than one set of connections is possible, this demonstrated the power of topological geometric thinking. When organic chemists deduced the existence of enantiomers by assuming that molecules could be represented by configurations of atoms in space, this likewise indicated the power of Euclidean 3D geometric thinking. The paradigm of expressing molecular structure in a geometric form allowed for extremely rapid progress of organic chemistry long before the appearance of spectroscopy and quantum mechanics. We now postulate that geometry at the topological and Euclidean level provides a cognitive structure for visualizing the most important properties of molecules. The geometric concept may be extended to the visualization of energy diagrams and energy surfaces. Perhaps not so obvious is the use of topological thinking to discern the sameness of objects and ideas. At the topological level, all tetrahedral configurations possess certain common properties, e.g., the existence of two enantiomers if the four atoms composing the structure are different.

However, the issue of representation of molecules by the position of atoms in space was a drastic paradigm shift at one time and was passionately resisted and attacked by some chemists. A quote in 1877 by Hermann Kolbe,[8] a distinguished organic chemist of his time, gives a view of the attitude of some in the chemical community. Here's what he had to say about the idea of even discussing the positions of atoms in space:

> "It is typical of the present time, when there is so little criticism and so much hatred of criticism, that two practically unknown chemists, one from a veterinary college and the other from an agricultural institute, pass

> judgment on the loftiest problems of chemistry, those which will probably never be solved, particularly the question of the position of atoms in space, and they undertake to answer these problems with an impudence and assurance that absolutely astonish the true scientist. This idea is now brought forth again, out of the store room harboring the errors of the human mind; by pseudoscientists who try to smuggle it, like a fashionably dressed and freshly rouged prostitute, into good society, where it does not belong."

As often occurs during periods of paradigm transition, the adherents of a field's reigning paradigm describe advocates of a "challenger" paradigm with a rhetorical vehemence that varies directly with the intellectual disequilibrium the new paradigm has produced. Planck's quote (*vide supra*) comes to mind! By the way one of the "pseudoscientists" that Kolbe was excoriating was van Hoff, who won the first Nobel prize in chemistry in 1900! Of course, he didn't win it for his ideas on the structure of atoms in space, because that idea required a paradigm shift which had not yet arrived in 1900.

We now can tie in the previously discussed ideas of Piaget and Kuhn to the notion of using geometry for structure in cognitive processing. Piaget's student at the concrete operational level of intellectual development can understand how to use Euclidean geometry for understanding a specific possibility of a structure, but at this intellectual level he or she will have trouble understanding how structures interconvert shapes based on a single shape. However, such a student can understand how shapes can change if an animation of the process allows its visualization, in which the changes in shape can be viewed in a connected fashion in "the present."

We can conclude that when a concrete operational student is studying chemical content, such as mechanistic pathways from reactants to transition states and conformational changes, *showing animations of these processes may help the student learn the content better*. Thus, both visualization and animation are expected to be helpful teaching and learning aids in the more difficult accommodation aspects of creating new knowledge. In principle, the student at the formal operational level of intellectual development does not need the animation and explicit visualization to understand structural changes. However, if the animations are engaging and interactive, these students will learn the *context* of the content more robustly. We have shown how to use these principles to produce effective IT modules for undergraduates (see J. *Chem. Educ.* **2005,** *82*, 1292-1301.) .

In summary, the conscious use of visualization and animation of content through topological and Euclidean geometry, structures, and structural change in time in cognitive processing provides a context for more effective learning by students at both the concrete operational and formal operational levels of development.

Survival skills, structures, and causal relationships.

> *"It has always been the task of formal education to set up behavior which would prove useful or enjoyable later in a student's life."*—B.F. Skinner

Perhaps the most important development in cognitive survival skills occurs when the mind can use structure to discern causal relationships between events occurring in the environment. When there is knowledge that an event of one type (the cause) is systematically related (*connected*) to a second or further events (the effects), it is possible to alter the environment by enhancing or inhibiting the probability of the occurrence of certain events. Without going into the philosophical pitfalls in the presumption that causal connections are valid, it is useful to note that both topological and Euclidean geometries, with their fundamental *connectivity* relationships between mathematical elements, provide an elegant structural basis for the cognitive representation of chemical cause-effect relationships. In chemistry we use the ideas of structure and energy to develop cognitive tools that provide us with theoretical models for the cause-effect relationships of structural changes with time. For organic reactions, for example, there are a relatively small set of mechanistic principles that apply to the energy costs of structural conversions, the pathways with the lowest energy cost being the fastest (if we consider free energy as the guide).

Perhaps nowhere is context more important than when attempting to learn how to assign causal relationships in science. Here, the instructor as expert and the student as novice may diverge widely in analyzing a strategy to solve a problem. The expert is accustomed to the actual values and magnitudes of certain causes and their resulting effects. The novice student rarely has a good feeling for these relative magnitudes. An interesting example of how this context issue arises in chemistry is the filling of energy levels. Consider the case of the electronic energy levels of an organic molecule when the energy levels are non-degenerate. How are electrons placed in the empty orbitals to produce a ground state? The students are taught that the electrons go into the orbitals two at a time, with spins paired according to the Pauli principle until all of the orbitals are filled. This filling scheme works because the electronic orbitals are far apart in energy and the bonding energy that is achieved is greater than the electron-electron repulsion that occurs when two electrons are stuffed in the same orbital. However, the rule of "two electrons, spin paired" is not followed when some orbitals are degenerate (or have similar energy). In this case because of the Pauli exclusion principle, the electron repulsion in more important than the bonding energy, and the electrons go in to different orbitals one at a time and only pair after all the degenerate orbitals are half-filled. When the degenerate orbitals are non-bonding, the situation is clear: the repulsion energy wins out (Hund's Rule). But what if two degenerate orbitals are "close" n energy but one is slightly more bonding than another? Here we have two apparently conflicting rules whose application requires a knowledge of the relative magnitudes of the repulsion energy versus bonding energy.

Armed with the above philosophy—combining the three pillars of good teaching and learning (content, context, and cognition), the topological similarities between education and research, and the use of geometry (composition, constitution, configuration, and conformation) for intellectual processing—I will describe briefly an important current model for education: constructivism (apologies for all the “c” words!). I will then show how one can employ the principles of this model as a basis for the effective application of IT to teaching and learning.

Constructivism: A research model that dares to prescribe some recipes for successful learning.

“A guy may think that he knows a lot, but he don’t have much knowledge if a lot of what he knows ain’t so.”—Anonymous

As I developed my own personal model of teaching, learning, and research, I began doing my own study on how students learn, because I wanted to understand how to base the development of IT materials on educational research to the greatest extent possible. I was pleased to discover that the conclusions of the three-pillar model were quite consistent with modern theories, particularly the model termed *constructivism*,[9] which can be summarized by several principles: (1) knowledge is constructed (not simply given or received) by an individual and is based on experience; (2) an individual’s prior knowledge must be modified in order for new knowledge to be constructed; (3) construction of new knowledge can be a stressful business for the individual when it requires the resolution of conflicts between prior knowledge and new knowledge. From this study, I concluded that the terms *knowledge construction* and *learning* may be used interchangeably. Thus, good teaching involves good learning (knowledge construction) by the student as the result of teacher-student interactions (application of the principles of integration of content, context, and cognition). It therefore follows that *there cannot be good teaching if there is no corresponding good learning*.

Constructivism postulates that knowledge creation is a personal construction by an individual. The learner is not a passive receiver, but an active constructor, of knowledge. A corollary of this postulate is that it is not possible simply to transfer knowledge into a student’s head intact; instead, students construct their own meaning from the words (audio clues) or pictures (visual clues) they hear and see. There is no learning that starts from scratch in the absence of preexisting knowledge and experience; there is no research that starts from scratch, either, without preexisting paradigms. The model of the instructor shifts from a “sage on the stage” who transfers knowledge to the student to a “guide on the side” who assists the student in knowledge construction.

The constructivism model is completely consistent with a model in which survival pressures (as in Darwinian natural selection) drive the cognitive processes that attempt to construct knowledge about how to act on the environment, and in which individuals construct new knowledge through the process of assimilation or accommodation (as in Piaget’s model of children’s intellectual development). We can use the terms developed by Piaget, assimilation and accommodation of knowledge, to describe the principles of constructivism. Constructivism posits that individuals can incrementally assimilate new knowledge if the latter is consistent with the preexisting knowledge; if it is inconsistent with preexisting knowledge, they must accommodate the new knowledge by modifying the preexisting knowledge. The preexisting knowledge may be both necessary building blocks of learning and an impediment to learning. This makes knowledge creation on the one hand a very individualistic event, since a learner’s specific preexisting knowledge depends on individual experience; on the other hand, knowledge creation most commonly occurs in a social setting such as a class, a laboratory, interactions with a mentor/instructor, peer interactions, etc.

A student's prior knowledge may impede his or her creation of new knowledge, and just as existing paradigms accepted by the scientific community may impede the creation and acceptance of new paradigms for that community. Prior misconceptions create intellectual conflicts and tensions that can be relieved only when learners become dissatisfied with the conflict and are driven to resolve it.

Educational research in constructivism has provided some useful principles that appear to apply broadly to the process of knowledge creation by individuals and provide guidance to the most effective pedagogical methods (Table 3).

Table 3. Pedagogic principles developed through constructivist educational research.

Principle	Manifestation in pedagogic practice
The individual is *actively* engaged in the learning process	active inquiry
The individual is guided by cognitive tools that organize the information for the learner	use of geometry to create structure
The individual is placed in a supportive environment of peers who are also engaged in the learning process	contextual support by socialization of content
The active engagement takes advantage of seeing, hearing, and touching to enforce the learning	employing senses for improving survival skills
The individual is involved in problem- or puzzle-centered inquiries, which probe and act on the environment	laboratory research for assimilation and accommodation

In implementing these student-centered principles, the instructor ideally takes a mixed role, part guide on the side and part sage on the stage. A constructivist instructor lets students create knowledge at their own pace but also shows them how to organize information and directs emphasis.

One of the important principles derived from constructivist educational research is that social interactions and discussion help students construct knowledge, change their knowledge, and reinforce their knowledge. The process of constructing meaning and creating new knowledge and gaining confidence in the validity of new knowledge is almost always embedded in a social setting of which the individual is a part. This aspect of constructivism leads to ideas of incorporating group learning, especially peer learning techniques, into the education process. When they hear other ideas from peers and discuss them among peers, students understand that the construction process differs from the pronouncement process of an authority. Individuals make choices about what new ideas to accept and how to fit them into their established views of the world.. Indeed, listening to students discuss ideas together is a great way for an instructor to learn what knowledge and culture exist in the students’ heads.

However, an instructor must understand that student-centered learning requires the student to take charge of his or her learning and to be responsible for it to the greatest extent possible. Some students may not be comfortable with this principle or even understand why it is being applied. They may figure that the instructor is being paid to teach them, believing that if they teach themselves, the instructor is slighting the student. For this and other reasons, it may be useful for an instructor to discuss matters of pedagogic philosophy and procedure explicitly with students at various times during a course, stressing that the constructivist approach represents a purposeful, theoretically informed strategy that is highly *student centered* and that should not be mistaken for disengagement from the teaching and learning process in the classroom.

Conclusions. Find out what works for you. Experiment!!

> *An ounce of experiment is worth a ton of theory.* Any Experimentalist

If you are completely satisfied with your teaching experiences and convinced that your students are receiving the highest possible quality education you can deliver, please read no further. However, if you feel that continuous quality improvement is a natural and never-ending quest, because there is always room for improvement, you may want to read on a bit for some suggestions of experiments to try. (For some of my own recent experiences in redesigning undergraduate courses, see J. *Chem. Educ.* **2005,** *82*, 1292-1301.)

Research in education in recent years has discovered a great deal about effective teaching and learning that can be of great use to instructors of undergraduates, especially faculty at research universities who teach large introductory courses.[10] It would be unbecoming for a scholar to ignore significant research that is relevant to a major area of his or her discipline. Research scientists should be no more willing to fly blind in their teaching than they are in their scientific research, where no new investigation is begun without an extensive examination of what is already known.

It is important that chemists know about atoms, molecules, electrons, and thermodynamics, but in my view teaching the content of chemistry is not as important as helping students *who are not likely to go on to a career in science* to reach some level of understanding of the *process of scientific inquiry and discovery*. Teaching and learning of chemistry provide only one exemplar, which could be replaced by physics, biology, or other sciences. The understanding that I would seek for students to take away from science course is *content-independent* and refers to core values of science and the process by which science employs old knowledge and creates new knowledge. The process by which a scientist creates new knowledge is generally termed *research*, the essence of the scientific process. The process by which a student creates new knowledge is termed *education*, the essence of the learning process. In research, to a certain extent, the scientist is an expert and is independent, acting as his or her own teacher/mentor, but always validating knowledge based on interactions and discussions with peers. In education, the student is a novice and requires an expert to serve as his or her teacher/mentor. This view leads to a natural identification of research and education as branches of the same intellectual tree; the only important difference is the level of the branches.

In research, to change a paradigm, a scholar must understand what the core of the community's paradigm is and attack it accordingly. In education, to change a student's preexisting knowledge, an instructor must understand what the core of this preexisting knowledge is and attack it accordingly. The most important single factor influencing learning is what the learner already knows. The instructor needs to know what the learner knows before he or she can effectively change that knowledge. Thus, an effective instructor of undergraduates needs not only sufficient scientific content knowledge on the one hand and pedagogical knowledge on the other hand, but also knowledge of the research showing the methods that reap benefits from the interplay between the two domains. We can consider preexisting knowledge as an example of an individual's cognitive paradigm. In this terminology, it is important to recognize the student's schema or the researcher's operating paradigm: by understanding the student's paradigm, one can use analogies to overlay new ideas and knowledge with preexisting knowledge. By understanding the student's paradigm, one can exploit effective learning techniques, i.e., either setting up cognitive dissonance by deliberately putting forth information that is in conflict with the student's preexisting beliefs, thus stimulating a cognitive context that seeks to remove the conflict, or using the paradigm to start from a point that has no conflict with preexisting knowledge and reinterpret the path to multiple conclusions.

One should not overlook a critical distinction between the models of cognitive development and paradigm formation discussed above: the former, derived from Piaget, involves processes within an individual mind, while the replacement of an old scientific paradigm by a revolutionary new one takes place through collective negotiation. This difference carries many implications that are undoubtedly worth exploring beyond the context of this essay. For the science instructor's purposes, however, one of these implications—the different forms of disequilibrium generated in professional communities and in individual minds—creates a fascinating challenge. Debates between proponents of old and new paradigms, as evinced in Kolbe's response to the idea of spatial configurations of atoms, may generate, as it were, more heat than light, more noise than signal; the energy that some scientists expend on derogating colleagues can be no more useful than friction in a mechanical device. When individual students perceive and express cognitive dissonance, however, a gifted instructor can help them transform that temporary discomfort into a motivating force. As in responses to evolutionary survival pressures, the sense of confusion when new data confound an old schema can have a constructive purpose, driving the student to build a new understanding on the scaffolding of the previous one. The art of guiding students lies in showing them ways to conserve, transform, and employ all the unruly energy of their growing minds.

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