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Piaget for Chemists

Explaining what "good" students cannot understand

It is apparent to anyone who has taught chemistry to college freshmen that a substantial number of students—particularly those in courses for non-science majors—find the subject difficult, in come cases incomprehensible. Unfortunately the fact that students have such difficulties is far more apparent than is the cause of this difficulty. This paper presents a hypothesis concerning the cause of the difficulty and suggests modifications in our approach to the teaching of chemistry that may ultimately lead to better instruction for a number of students.

The thesis to be developed is that available evidence strongly suggests that a substantial number of entering college students—perhaps as high as 50% in courses for non-majors—are unable to function at an intellectual level which is described by Piaget as *formal operational.* But the content of chemistry and the approach that we normally take in teaching chemistry require that the student operates at this formal operational level if he is to comprehend the concepts that are presented.

Before discussing what is meant by formal operational thought, let me relate a very few anecdotes to illustrate the kind of difficulties which I believe to be related to this discussion.

The first incident which I will relate occurred during the discussion of an electrolysis experiment. The question that I had posed was how we could be sure that the gases had come from the water and not from the sodium carbonate which we had used as an electrolyte. After all, we had no gas produced until we added the electrolyte; why not suppose that the electrolyte is the source of the gas? Midway in the discussion the student gave me a very strange look and said, "Do you mean that the wet water is *disappearing* and that it is turning into those gases that you can't even see! Is *that* what you mean by the gases coming from the water? I don't believe it! It just isn't possible! Water isn't *anything* like those gases."

A second incident occurred midway through a *second* semester course for home economics majors. I had given an exam and those who scored low started visiting. I tried to find out what was wrong. I asked such questions as, "Just tell me in your own words, what is the difference in what we are representing by H^+, H, and H_2?" Some few attached a name of ion, atom, and molecule to the three but none of the students who came to me seemed to have any conception of the difference in the particles represented. "Look," I said, "Tell me what this chemical sentence is saying: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$." Most students had no idea. On the final examination in the course, fewer than 50% of the students seemed to comprehend that it was Cl^- that was in table salt and not Cl_2—or that there is a difference in the two.[1]

The third "incident" is a general observation rather than a specific event. Over the years I have observed that any concept which involves a ratio is extremely difficult for many students; density, velocity, acceleration, molarity, and reaction rate are names for a few of these concepts. Students are able to memorize an algorithm for making numerical calculations of these quantities but appear to have such poor comprehension of the idea that they are unable to apply the concept to any problem different from those analyzed and discussed in class. (For example, students who have learned to calculate density from mass and volume data are frequently unable to answer simple questions such as, "Water has a density less than that of sulfuric acid. Which would have the greater volume, 100 g of water or 100 g of sulfuric acid?")

If I thought that the misconceptions—better yet, no-conceptions—that I have related were due solely to my inept teaching, I would not be reporting them. And contrary to what some professors choose to believe, these are not students who make no effort to learn. These are "good" students who make a conscientious effort to achieve. But these students just cannot seem to understand abstract ideas such as atoms, molecules, and ideal gases. Are they just "dumb?" I think so. But not in the same sense that we normally say that a person is "dumb" or "stupid." I believe that these are students who have not progressed in their intellectual development to the stage of formal operations.

Some of you are familiar with the work of the Swiss psychologist, Jean Piaget. For those who are not, a three paragraph summary must suffice to put things into perspective.

Piaget describes intellectual development in terms of four stages; sensory-motor, pre-operational, concrete operational, and formal operational. According to Piaget, we would expect students to enter the stage of formal operational though at about the age of 12 and to essentially complete their basic intellectual development by the age of 15. Unfortunately, evidence from a number of studies suggests that this is not so. Lovell tested a number of students in England and found that only between 23 and 37% of a sample composed of 39 grammar school pupils, 10 training college students, and 3 adults demonstrated formal thought *(1).* In a study done by Dale in Australia, only 25% of the 15 year old students in his sample were able to completely solve a task designed to measure formal thought *(2).* A widely publicized study done a few years ago at the University of Oklahoma indicated that 50% of the college freshmen tested were functioning completely at Piaget's concrete operational level and that only 25% of the sample could be considered fully formal in their thought *(3).* Studies by Elkind *(4)* and by Tower and

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This paper is a modest revision of "On Atoms, Love and Providence: Things "Good" Students Just Can't Understand," which was presented at the 8th Great Lakes Regional Meeting of ACS, Purdue University, June 3-5, 1974.

[1] At the 8th Great Lakes Meeting, Professor Bassam Shakhashiri used an example in a description of his Chem Tips Survey which may represent the same lack of understanding at Wisconsin. The following item on the survey had the response pattern shown by the percentages in parentheses: "Which of the following species can act as an oxidizing agent in aqueous solution?

Cl^- (30) NH_3 (7) Na (7) Fe^{3+} (53)

It is quite possible that many of the 30% who selected Cl^- perceive no difference between Cl^-, Cl, and Cl_2.

Wheatley *(5)* showed that only about 60% of college freshmen tested believed that the volume of a ball of clay remained constant when the clay was rolled into a sausage. Implications of these studies become clear when we further compare the intellectual functioning of the student in the concrete operational stage of development with one who is formal.

To begin, it helps to keep in mind that "concrete operations *are* concrete, relatively speaking; their structuring and organizing activity is oriented towards concrete things and events in the immediate present" *(6)*. The concrete operational student does not think in terms of possibilities and is not able to understand abstract concepts which depart from concrete reality. The formal operational student, however, "begin(s) thinking in terms of what *might* happen and to envision all the changes that are possible. It enables him to reason without visual props" *(7)*. To say that a student who has not reached the stage of formal operations cannot reason or solve problems is misleading. He can. But the starting point for the concrete operational student is always the real rather than the potential. His reasoning is always based on real observations and is limited to extrapolations from these sensory experiences. He does not delineate all possibilities and think of the observed as simply a special case of the possible.

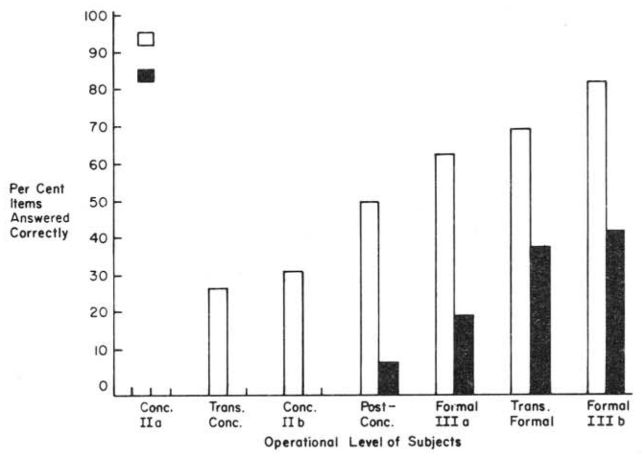
Since even those individuals who *have* developed to the level of formal operations normally revert to concrete operational thought when they encounter an unfamiliar area, it is only fair that examples be given to help clarify the distinctions to be made.

One distinction between concrete operational thought and formal operational thought is that the former is in terms of concrete experience while the same logical operations applied to abstractions would be characteristic of formal operational thought. For example, a student who operates at the concrete operational level can correctly answer the question, "Are there more green spheres or more plastic spheres?" after he has seen the instructor place several white and several green plastic spheres in a box. However, only those students who operate at the formal level respond correctly when they are told, "'Some of the molecules in solution are blue,' said the Prof. One student responded, 'Then all of the molecules are blue.' A second student comments, 'Some of the molecules are blue,' and a third states, 'None of the molecules is blue.' Who is right?"

Similarly students who operate at the concrete level can easily order a group of sticks from shortest to longest. However, when told, "Bill is taller than John; Bill is shorter than James; who is tallest of the three?" only those students who have begun to use formal operations can respond correctly.

Once formal operations are reached, subjects begin thinking in terms of possibilities and are able to systematically consider all possibilities in a given situation. One of the tasks used to distinguish between concrete and formal subjects involves presenting the subject with four numbered bottles filled with colorless solutions (the solutions are dilute sulfuric acid, "oxygenated water," pure water, and sodium thiosulfate) and a dropper bottle filled with a solution labeled "g" (potassium iodide). The subject is then asked to "use what is in the numbered bottles to produce a yellow color when "g" is added." The procedure followed by students at the concrete operational level tends to be trial and error; all possible combinations are not examined—indeed, it appears that the subject is not capable of identifying the possible combinations. By contrast, the procedure followed by those who are formal is systematic; the possible combinations are eliminated in orderly fashion.

A third characteristic of formal operations is recognition of the logical necessity: "All other things being equal." This may be illustrated by another task used to determine whether students operate at the formal operational level. The flexible rods task involves giving the student weights and several metal rods which differ in length, cross section, and composition. The student is asked to find what factors will affect the amount that the rods will bend.



A comparison of success on concrete and formal concepts with chance-eliminated, pooled data. Taken from Lawson *(8)*.

Typical of the concrete response is the student who will hang equal weights on a short, thick rod and a long, thin rod to "prove" that "longer rods bend more." Moments later he may use the *same* materials to "prove" that "thin rods bend more." However, the formal student "controls variables;" i.e., he sees the necessity for "all other things being equal" before drawing conclusions about the effect of some manipulated variable on the bend of the rod.

Although there are other distinctions between concrete and formal thought, these should suffice.

Based on Piaget's model of intellectual development, Lawson *(8)* has suggested that there are certain concepts that are understandable to students who are still at the concrete operational stage of development while other concepts are understandable only to those students who have reached formal operations.

Lawson has shown that there is a direct relation between the learning of formal concepts and the level of intellectual development as defined by Piaget. The figure shows the percent of concrete concept questions and formal concept questions that were answered by high school students at various stages of intellectual development. Of particular interest is the fact that no formal concept questions were answered correctly by any student who had not progressed to the level that Lawson called "post-concrete." (This represents a level of transition from concrete to formal thought.) Furthermore, only those students who showed evidence of substantial development of formal thought (beyond Piaget's level of IIIA) were able to answer as many as half of the formal concepts questions (the percentages shown in the figure are somewhat lower since they have been corrected for guessing.)

But still, one might ask, where is the problem? How much of what we teach in chemistry actually requires formal thought? In my judgment, a great deal—and I am not alone. In a paper discussing the level of thought required for success on various science questions, Robert Karplus comments *(9)*

> I was surprised when I originally examined eight teacher-made biology tests and failed to locate any questions that, in my judgment, invited formal thought. . . . (But in chemistry) I found problems requiring formal thought everywhere I looked. I had difficulty locating items that could be solved on the concrete level and did not depend on recall of facts concerning the properties of specific elements and compounds.

With no attempt to be exhaustive, I have listed examples of performances which are commonly expected of beginning chemistry students which, in my judgment, *can be performed by students who are not formal* in their thinking and I have contrasted these with descriptions of related performance which I believe would require formal thought. These are presented in the table.

In looking at the list that I have prepared, I am increasingly aware that I tend to emphasize those performances that are found on the "can't do" side of the ledger. I cringe every time I put an item on a test which requires no more than rote memory. If my arm-chair judgment is correct, then one would predict that achievement in a chemistry course taught by me would be substantially related to a student's level of intellectual development as measured by Piaget's tests.

This past semester, a random sample of 20 students was selected from those students enrolled in the course that I supervised. Seventeen of the sample were available for testing with a battery of Piaget tasks administered by three graduate students in science education. Scores on this battery of tasks were then correlated with the total points earned in the course using the Pearson product-moment correlation. The best estimate of the correlation obtained was 0.8 *(10)*.

To what extent this relationship would hold in other chemistry courses is uncertain but I think that it would be high. As a part of the work we were doing this past semester, 33 students from a number of freshmen courses were tested with the same battery of Piaget tasks, and scores on this battery were correlated with scores on a chemistry placement test that had been administered the previous semester. Unfortunately, the students in this sample were not representative of students in the chemistry classes; a large proportion of them were among the better students. This restriction of range in the sample plus the time interval between the administration of the chemistry placement exam and the Piaget tests should result in an obtained estimate of correlation lower than what actually exists between the two measures. Still, the correlation was substantial at 0.7 *(11)*.

What I am saying is that *the available evidence strongly* suggests that there are a substantial number of entering college students who do not function at the formal level—perhaps as high as 50% in freshman courses for non-science majors—but that the content of chemistry and the

Competencies Commonly Expected of General Chemistry Students Which Can Be Understood by Students Who Are Not Formal Operational

Things that students who have not reached formal operations CAN DO	Things that students who have not reached formal operations CAN'T DO
1. Any routine measurement or observation.	1. Measurement of density, heat of reaction, and other "derived" quantities which are not observed directly.
2. Make inferences which are direct extrapolations from observations; e.g., "wood objects burn" as an inference following the observation of several wooden objects which burn.	2. Make inferences which are "twice removed" from observations; e.g., "the paper, the wood, and the gasoline all burned; these are carbon compounds; carbon compounds burn."
3. Comprehend *the idea that the* ratio of the mass (or volume) of hydrogen to the mass of oxygen in water is constant. (This should be in the "can do" list only if the idea is developed from actual observation of data or through a procedure which enables the student to understand the source of the data.)	3. *Reason that the constancy of* mass ratios and volume ratios in substances such as water leads to a conclusion that compounds can be represented as particles made up of atoms combined in definite proportions.
4. Construct cooling curves for pure and impure substances and infer from the shape of the cooling curve of an unknown substance whether the unknown is pure (or a eutectic mixture) or impure.	4. Explain why the plateau occurs in the cooling curve of a pure substance during the phase change.
5. From a description of the behavior of a gas using a physical model (such as the Molecular Dynamics Simulator), predict effects of increasing temperature on the average kinetic energy and distribution of energies among molecules of a gas.	5. From the postulates of the Kinetic Theory, predict those conditions of temperature and pressure under which real gases will not obey the ideal gas law.
6. From the definition of molarity, prepare 1000 ml of a 1 M solution.	6. From the definition, prepare 25 ml of a 2.5 M solution. Prepare 1000 ml of a 0.25 M solution from a 3 M stock *solution*.
7. Follow a set of rules to find the empirical formula of a compound.	7. Understand why following the rules will result in the empirical formula.
8. Conceive of atomic weight as the mass of a given number of molecules; i.e., the atomic weight is the weight (mass) of 602,000,000,000,000,000,000,000 atoms.	8. Conceive of atomic weight as the ratio of the mass of one atom to the mass of some other atom which is selected as a standard.
9. Use factor-label to solve problems *in instances where the* units provide an indication of the operations to be performed.	9. Use ratio and proportions to *solve problems which will not* fit into a "type" problem which has been memorized.
10. Balance equations, write formulas, calculate molecular weights, etc. using set rules.	10. Derive the rules for balancing equations, writing formulas, etc. from general principles such as the law of conservation of mass or the law of definite proportions.
11. Conceive of an acid as any substance that will turn litmus red.	11. Conceive of an acid as a proton donor or electron pair acceptor.
12. Demonstrate that a solution contains ions by showing electrical conductivity; measure the current flowing in a solution; show that the mass of metal deposited on an electrode increases regularly with the current or with time.	12. Predict changes in time that would be needed to compensate for an observed change in current; use the amount of current and the time to calculate the number of atoms of metal deposited.
13. Apply rules concerning reaction rates to predict changes in rate which would result from changes in temperature and concentration.	13. Explain the effect of temperature changes or concentration change in terms of the collision theory.
14. Observe the effect of a change in temperature, concentration, or pressure on the concentration of some component of a system originally at equilibrium and predict the nature of the system when additional changes of the same type are made.	14. Predict the effect on some *other* component of the system when these same changes in temperature, pressure, or concentration are made. Given the expression for the equilibrium constant, predict the effect on the concentration of one component of the system when the concentration of another component is changed.
15. Knowing the volume of base *needed to neutralize 1 g of* acid, calculate the volume of base need to neutralize any amount of acid.	15. Knowing the concentration of base and the volume needed to neutralize a given volume of acid, calculate the concentration of the acid.
16. Place various metals into a solution containing a metal ion and use the data to place the metals above or below the metal in solution. (Begin constructing an activity series.)	16. Use data from a series of experiments such as this where some metals appear only in ion form while others appear as metals to construct an activity series.

None of the above have been tested to establish that concrete operational individuals can perform the tasks indicated on the left while tasks indicated on the right can be performed only by formal operational individuals. The list represents hypothesized difference and is based on the author's judgment of the mental activity required to accomplish the task. It should also be noted that what is described as an intellectual dichotomy is a convenient division of a continuum. As a consequence the tasks which are described in both lists vary in difficulty.

approach that we normally take in teaching chemistry require that the student operate at the formal level if he is to comprehend the concepts that are presented. If this assessment is correct, then we clearly have a problem. Actually, I expect the "if" of that statement to elicit far less agreement than the "then." My colleague, Derek Davenport, has alluded to the same problems which concern me even though we approach the issue from quite different perspectives. To quote Derek, "Under the post-Sputnik backlash the content of chemistry courses was dramatically changed. This was good since much useless lumber had accumulated. At the same time the intellectual level was raised to the point where average students (and many of the T.A.'s) were frequently out of touch with reality. *Unknown facts were being explained in terms of inscrutable theory and varying degrees of chaos resulted.* Like the Red Queen one had to run fast to merely stay in the same place and twice as fast to keep up with the avant-garde." *(12)* (emphasis added).

To the extent that the changes that we have observed in science teaching have been in the direction of explaining chemical facts that students have had no opportunity to experience in terms of inscrutable theory, we have certainly made science more difficult for those "good" students who cannot understand abstractions. But in my judgment, a large part of chemistry *is* abstractions. The temptation to return to a course based on the blind memorization of a catalog of descriptive chemical facts is as repugnant to me as the continuation of courses based on the blind memorization of inscrutable theory. The alternative, in my judgment, is to recognize why the theory is inscrutable; i.e., recognize that a large portion of our students operate below the formal level and approach the teaching of chemistry in such a way that we either skirt the problem or overcome it. We can skirt the problem if we can make what we are trying to teach accessible to those students who are not formal thinkers and we can overcome it if we can encourage and assist students in becoming formal. I want now, to deal with these two issues.

Let me describe what I mean by making content available to the concrete student. In the table, I have suggested that the concept of an acid as anything that will turn litmus red is a concrete concept. The meaning of the concept is easily apprehended from sensory observation and requires simple classification skills. But I have also suggested that the concept of an acid as anything that will produce hydrogen ions in water solution (Arrhenius), as a proton donor (Bronsted-Lowry), or as an electron-pair acceptor (Lewis) is formal. These meanings of acid cannot be made clear through the senses directly since there is no way to sense protons or electron pairs. Rather, this concept of acid can have meaning only through imagination or through logical thought about the nature of molecules which interact.

Before I proceed, let me offer a caution to those of you who are saying, "Hogwash! I have no trouble teaching students Bronsted-Lowry or Lewis theories of acids and bases." Before you arrive at that conclusion too quickly check carefully to be sure that the students who have "learned" these concepts are not simply parroting words without apprehending meaning to those words. What I have reference to here is *meaningful* learning rather than rote memory.

I have suggested—and believe—that formal concepts are not really accessible to students who are not formal in their thought but I do believe that we can enable students at the concrete level to acquire surrogate concepts which can substitute for the real thing, enable them to handle many (but not all) of the problems that we foist upon them, and make the transition from the surrogate to the real fairly easy at some later time. The solution, I believe, is to provide extensive experience with concrete props which model the abstract concept. We do this now but we do not do it enough. In the case of the concept of an acid, for example, I believe that we can do very well if we made extensive use of physical models in which we show students a ball representing the proton being removed from the acid substrate. The model is concrete and the student can imagine the process which we describe in terms of this model.

In addition to physical models manipulated by the student, one can make use of films to provide macroscopic models of microscopic systems. Several examples of such models can be seen in the CHEM Study films; for example, the use of the ripple tank to demonstrate interference patterns in "Crystals and Their Structure," the use of molecular models to demonstrate adsorption of wave energy in "Molecular Spectroscopy," and the animation used to describe molecular behavior in "Introduction to Reaction Kinetics." It is probably true that the concept that the student develops when he sees such models is not exactly the concept that we are trying to teach but it is a reasonable approximation and has considerable utility in handling various problems which the student may be asked to solve.

It takes no imagination to see that the possibilities for using physical models to provide meaning to abstract concepts in chemistry are very large. What seems to take imagination is for the instructor (who is certain to be formal in his thinking) to appreciate that it is worth the time and effort to play with balls and sticks and to have students do likewise. But there is at least some evidence to show that the extra time is well spent unless you are simply interested in students memorizing bits of information. In a study done in West Virginia, it was found that students who were required to build physical models to represent the reactants and products for every equation discussed in lecture scored about 24% higher on all tests given during the semester than did students who did not use the models *(13)*. It should be noted that when only memory level test questions were considered, the students who did not use the models did slightly better (about 5%) but for questions that involved logical thought, the students who had used the models scored from 30–65% higher. On a retention test given to students who continued the course the following semester, the difference between the two groups was essentially the same.

There are other strategies which can be used in the teaching of chemistry which make the content more accessible to students who are not fully formal in their thinking. Certain concepts can be approached in various ways and in some instances, one approach requires more formal thought than another. As an example, I would argue that the presentation of oxidation and reduction as a loss and gain of electrons requires formal thought whereas the presentation of oxidation and reduction in terms of a gain and loss in oxidation number requires only concrete thought. On first examination this may seem preposterous since both definitions of the concept are in terms of some kind of gain or loss. But consider that oxidation number is presented as a bookkeeping device in which the student learns a set of rules which are easily applied to find the oxidation number of the atom and then the change in oxidation number. It is not necessary for the student to imagine anything about the nature of the atoms (which are decidedly *not* concrete) in order for the student to apply the rules to balance equations involving oxidation and reduction or to arrive at any of the conclusions that we normally want to impart in the course of our instruction. Further, teaching oxidation and reduction in this way does not interfere with the student's latter association of oxidation with the loss of electrons when—say in the unit on electrochemistry—the student makes some concrete observations which can easily be extrapolated to the conclusion that the increase in oxidation number of an atom may be the result of a loss of electrons. But the understanding of oxidation in terms of loss of electrons requires imagination of what has never been seen and an understanding of a postulatory-deductive system; namely, atomic theory. Therefore, it seems to me that this concept of oxidation can only be understood by students who are formal operational.

The factor-label (sometimes called dimensional analysis or unit analysis) approach to solving problems in chemistry is widely used because teachers who have tried it find that it works whereas ratio-and-proportion approaches are easily confused by students. For a student to consistently apply the method of ratio-and-proportions to chemical problems correctly, the student must be capable of formal thought. Since all stoichometic problems involve the concept of ratios and proportions, I am convinced that any student who fully understands what is going on must be operating at the formal level, regardless of how he solves the problem. But factor-label provides an almost foolproof procedure for solving stoichiometric problems correctly without the necessity for formal thought. Furthermore—and I consider this to be important—the procedure organizes the chemical facts in the problem in such a way that it may lead the student to see the reasoning that characterizes the solution. At the very least, it does not interfere with the perception of the logical relationships implied in the equation and assumed in the solution of the problem.

I am firmly convinced that we can identify many other topics in chemistry which are generally presented in a manner that requires formal thought but could be presented in such a way that a reasonable facsimile of the idea is available to those students who have not reached the level of formal operations. Still, I believe that it is misleading to assume that anyone who is not formal in their thinking can "understand" chemistry. Chemistry, and most of science, is formal by its very nature. Recognizing this, we cannot continue to duck our responsibility for the development of formal thought.

Since Piaget suggests that students should develop formal thought by the age of 15 and since we know that many people do, we might ask, "Why do roughly half of the non-science students in colleges fail to exhibit formal operational thought?" One possible explanation—and one that should not be completely ignored—is genetic inheritance. However, there are several observations (e.g., that a larger proportion of boys exhibit formal thought than girls) that suggest other reasons. There are some studies which show that education can lead to improvement in formal thinking *(3)*. We are in the exploratory stage of research in this area but there are consistencies that seem to be emerging. First, the inclusion of concrete experience—i.e. opportunities to actually touch, smell, see, and manipulate materials that would lead to the concept—appears to be important. But concrete experiences are *not* particularly useful if all the student does is touch, smell, see, and manipulate without being forced to think about what he is doing. Because this is what happens in most of our lab work, it does little good. It would appear that those educational experiences which encourage the intellectual debate of ideas, the weighing of evidence, and an emphasis on "making sense" out of observed facts are ones that lead to the development of formal thought. But these educational experiences are time consuming, require a great deal of interaction among students or between teacher and student, and are painfully frustrating for both the student and the teacher. Students who are not already at the formal operational level are likely to find the experience so frustrating that they want to give up and the instructor is likely to regard these students as too stupid to understand the material anyway. If the course is one for majors, these students will flunk because they cannot keep up—and probably should. If the course is a service course for elementary education majors or nurses or home economics majors, a more common response is to assume that these people are too dumb or too disinterested to understand chemistry and the course is designed so that the emphasis is on recall of information which seldom has meaning to the student. If the student makes any reasonable effort and manages to recall a fair porportion of the memorized material without getting it too badly confused, he is given the benefit of the doubt and passed.

We seem to be on a carrousel. We present the material at an abstract level with few concrete props for even the better students to grasp; because the students are intellectually unable to understand the ideas, they memorize; we give a test from which we discover that students have learned only what can be learned by memory; we conclude that the students cannot really think so we had better just be content with teaching what we can teach by rote; because we limit our instruction to that which involves rote memory, students are never forced to develop their thinking to the level of formal operations; because they do not develop to the level of formal thought, they cannot understand the abstract material we present.

I believe that we can make considerable progress in the teaching of chemistry to non-science students when we recognize the vast number of ideas in chemistry which are presented in a manner which requires formal thought for even an approximate understanding of the concept. We can search for alternative approaches to these ideas which rely less on formal operations. However, since science is, by its very nature formal, we must also make a conscientious effort to enhance the intellectual development of college students. We cannot assume that "good" students *are* formal but we can certainly help them to *become* formal.

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