

AN INTRODUCTION TO CRITICAL THINKING

by

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Introduction to Critical Thinking

Critical thinking is an important and vital topic in modern education. All educators are interested in teaching critical thinking to their students. Many academic departments hope that its professors and instructors will become informed about the strategy of teaching critical thinking skills, identify areas in one's courses as the proper place to emphasize and teach critical thinking, and develop and use some problems in exams that test students' critical thinking skills. This critical thinking manual has been prepared to inform and aid you to accomplish these things, and it has been kept brief and straightforward so that all faculty members will have the time and opportunity to read it and follow the suggestions it contains.

Purpose and Rationale of Teaching Critical Thinking

The purpose of specifically teaching critical thinking in the sciences or any other discipline is to improve the thinking skills of students and thus better prepare them to succeed in the world. But, you may ask, don't we automatically teach critical thinking when we teach our subjects, especially mathematics and science, the two disciplines which supposedly epitomize correct and logical thinking? The answer, sadly, is often no. Please consider these two quotations:

"It is strange that we expect students to learn, yet seldom teach them anything about learning." Donald Norman, 1980, "Cognitive engineering and education," in *Problem Solving and Education: Issues in Teaching and Research*, edited by D.T. Tuna and F. Reif, Erlbaum Publishers.

"We should be teaching students how to think. Instead, we are teaching them what to think."
Clement and Lochhead, 1980, *Cognitive Process Instruction*.

Perhaps you can now see the problem. All education consists of transmitting to students two different things: (1) the subject matter or discipline content of the course ("what to think"), and (2) the correct way to understand and evaluate this subject matter ("how to think"). We do an excellent job of transmitting the content of our respective academic disciplines, but we often fail to teach students how to think effectively about this subject matter, that is, how to properly understand and evaluate it. This second ability is termed critical thinking. All educational disciplines have reported the difficulty of imparting critical thinking skills. In 1983, in its landmark report *A Nation at Risk*, the National Commission on Excellence in Education warned:

"Many 17-year-olds do not possess the 'higher-order' intellectual skills we should expect of them. Nearly 40 percent cannot draw inferences from written material; only one-fifth can

write a persuasive essay; and only one-third can solve a mathematics problem requiring several steps."

While we as professors have the ability ourselves to think critically (we had to learn these skills to earn advanced degrees in our disciplines), many students--including our own--never develop critical thinking skills. Why? There are a number of reasons. The first goal of education, "what to think," is so traditionally obvious that instructors and students may focus all their energies and efforts on the task of transmitting and acquiring basic knowledge. Indeed, many students find that this goal alone is so overwhelming that they have time for little else. On the other hand, the second goal of education, "how to think" or critical thinking, is often so subtle that instructors fail to recognize it and students fail to realize its absence.

So much has become known about the natural world that the information content of science has become enormous. This is so well known that science educators and science textbook writers came to believe that they must seek to transmit as much factual information as possible in the time available. Textbooks grew larger and curricula became more concentrated; students were expected to memorize and learn increasingly more material. Acquisition of scientific facts and information took precedence over learning scientific methods and concepts. Inevitably, the essential accompanying task of transmitting the methods of correct investigation, understanding, and evaluation of all this scientific data (that is, critical thinking) was lost by the roadside. This situation became especially severe in primary and secondary education, and over the last decades there has been a well-known decline in the math and science ability of students in our country compared to other industrialized countries. Studies have shown that our students abilities in math and science begin on level with students in other countries, but then progressively decrease as they make their way through our educational system. By the end of high school, United States students rank among the lowest in the industrialized world in math and science achievement. We in introductory college science education inherit these students and have to deal with their deficiencies in scientific and critical thinking.

In retrospect, it seems obvious that when the information content of a discipline increases, it becomes even more vital to spend time, not learning more information, but learning methods to acquire, understand, and evaluate this information and the great amount of new information that is not known now but will surely follow. Frankly, it is counterproductive to simply memorize and learn more new and isolated facts when future facts may eventually displace these. Thus, our science education policy has been completely backward, teaching more science facts and less scientific method rather than the converse. The errors of primary and secondary education in math, science, and other disciplines during the last forty years are now well known and are currently being addressed. The latest science books, for example, emphasize critical thinking and the scientific method. They focus on teaching students the proper ways to obtain new reliable knowledge for one's self, not on engendering factual overload. Curriculum reforms in science, such as Project 2061 of the AAAS and Scope, Sequence and Coordination of the NSTA, are also being instituted. It will be another generation before these textbook and curriculum reforms will have achieved results, if ever, and until then we must be aware of students' lack of critical thinking skills and of our need to enhance them. (It is accepted, one assumes, that students entering college should already have mastered all basic critical thinking skills; that is, they should have learned these skills during their primary and secondary education and thus be able to bring them with them into the college math and science classroom. The fact that this manual has been prepared is an indication that students have not learned these skills. We may be the last opportunity such students have to appreciate and learn critical thinking.)

A final rationale for critical thinking is explained by William T. Daly (1990) in a short article, "Developing Critical Thinking Skills." He says that

"the critical thinking movement in the U.S. has been bolstered and sustained by the business community's need to compete in a global economy. The general skill levels needed in the work force are going up while the skill levels of potential employees are going down. As a result, this particular educational reform movement . . . will remain crucial to the education of the work force and the economy's performance in the global arena. This economic pressure to teach critical thinking skills will fall on educational institutions because these skills, for the most part, are rarely taught or reinforced outside formal educational institutions. Unfortunately, at the moment, they are also rarely taught inside educational institutions."

Definition of Critical Thinking

Critical thinking means correct thinking in the pursuit of relevant and reliable knowledge about the world. Another way to describe it is reasonable, reflective, responsible, and skillful thinking that is focused on deciding what to believe or do. A person who thinks critically can ask appropriate questions, gather relevant information, efficiently and creatively sort through this information, reason logically from this information, and come to reliable and trustworthy conclusions about the world that enable one to live and act successfully in it. Critical thinking is not being able to process information well enough to know to stop for red lights or whether you received the correct change at the supermarket. Such low-order thinking, critical and useful though it may be, is sufficient only for personal survival; most individuals master this. True critical thinking is higher-order thinking, enabling a person to, for example, responsibly judge between political candidates, serve on a murder trial jury, evaluate society's need for nuclear power plants, and assess the consequences of global warming. Critical thinking enables an individual to be a responsible citizen who contributes to society, and not be merely a consumer of society's distractions.

Children are not born with the power to think critically, nor do they develop this ability naturally beyond survival-level thinking. Critical thinking is a learned ability that must be taught. Most individuals never learn it. Critical thinking cannot be taught reliably to students by peers or by most parents. Trained and knowledgeable instructors are necessary to impart the proper information and skills. Math and science instructors have precisely this information and these skills. Why?

Critical thinking can be described as the scientific method applied by ordinary people to the ordinary world. This is true because critical thinking mimics the well-known method of scientific investigation: a question is identified, an hypothesis formulated, relevant data sought and gathered, the hypothesis is logically tested and evaluated, and reliable conclusions are drawn from the result. All of the skills of scientific investigation are matched by critical thinking, which is therefore nothing more than scientific method used in everyday life rather than in specifically scientific disciplines or endeavors. Critical thinking is scientific thinking. Many books and papers describing critical thinking present it's goals and methods as identical or similar to the goals and methods of science. A scientifically-literate person, such as a math or science instructor, has learned to think critically to achieve that level of scientific awareness. But any individual with an advanced degree in any university discipline has almost certainly learned the techniques of critical thinking.

Critical thinking is the ability to think for one's self and reliably and responsibly make those decisions that affect one's life. Critical thinking is also critical inquiry, so such critical thinkers investigate problems, ask questions, pose new answers that challenge the status quo, discover new information that can be used for good or ill, question authorities and traditional beliefs, challenge received dogmas and doctrines, and often end up possessing power in society greater than their numbers. It may be that a workable society or culture can tolerate only a small number of critical thinkers, that learning,

internalizing, and practicing scientific and critical thinking is discouraged. Most people are followers of authority: most do not question, are not curious, and do not challenge authority figures who claim special knowledge or insight. Most people, therefore, do not think for themselves, but rely on others to think for them. Most people indulge in wishful, hopeful, and emotional thinking, believing that what they believe is true because they wish it, hope it, or feel it to be true. Most people, therefore, do not think critically.

Critical thinking has many components. Life can be described as a sequence of problems that each individual must solve for one's self. Critical thinking skills are nothing more than problem solving skills that result in reliable knowledge. Humans constantly process information. Critical thinking is the practice of processing this information in the most skillful, accurate, and rigorous manner possible, in such a way that it leads to the most reliable, logical, and trustworthy conclusions, upon which one can make responsible decisions about one's life, behavior, and actions with full knowledge of assumptions and consequences of those decisions.

Raymond S. Nickerson (1987), an authority on critical thinking, characterizes a good critical thinker in terms of knowledge, abilities, attitudes, and habitual ways of behaving. Here are some of the characteristics of such a thinker:

- uses evidence skillfully and impartially
- organizes thoughts and articulates them concisely and coherently
- distinguishes between logically valid and invalid inferences
- suspends judgment in the absence of sufficient evidence to support a decision
- understands the difference between reasoning and rationalizing
- attempts to anticipate the probable consequences of alternative actions
- understands the idea of degrees of belief
- sees similarities and analogies that are not superficially apparent
- can learn independently and has an abiding interest in doing so
- applies problem-solving techniques in domains other than those in which learned
- can structure informally represented problems in such a way that formal techniques, such as mathematics, can be used to solve them
- can strip a verbal argument of irrelevancies and phrase it in its essential terms
- habitually questions one's own views and attempts to understand both the assumptions that are critical to those views and the implications of the views
- is sensitive to the difference between the validity of a belief and the intensity with which it is held
- is aware of the fact that one's understanding is always limited, often much more so than would be

apparent to one with a noninquiring attitude

- recognizes the fallibility of one's own opinions, the probability of bias in those opinions, and the danger of weighting evidence according to personal preferences

This list is, of course, incomplete, but it serves to indicate the type of thinking and approach to life that critical thinking is supposed to be. Similar descriptions of critical thinking attributes are available in the very extensive literature of critical thinking. See, for example, *Teaching Thinking Skills*, 1987, edited by J. B. Baron and R. J. Steinberg; *Developing Minds: A Resource Book for Teaching Thinking*, 1985, edited by A. L. Costa; *The Teaching of Thinking*, 1985, edited by R. S. Nickerson and others; *Critical Thinking, Fifth Edition*, 1998, by B. N. Moore and Richard Parker, and *Critical Thinking, Second edition*, 1990, by John Chaffe. These books are representative of the genre.

Relationship of Critical Thinking to the Scientific Method

Because of the identification of critical thinking as scientific thinking, it is reasonable to conclude that math and science courses are a good place to learn critical thinking by learning the scientific method; unfortunately, this is not always true. Good scientists who conduct science must practice critical thinking, and good science teachers usually teach it, but few ordinary individuals learn the scientific method, even those who successfully take a number of science classes in high school and college. This is because, as discussed above, science in the United States is often poorly taught as a fact-based discipline rather than as a way of knowing or method of discovery. As incredible as it may seem, studies reveal that 3% of the U.S. population is scientifically literate, down from 5% about twenty years ago. Thus, it does not appear that science alone will teach critical thinking to the masses. In fact, critical thinking programs are almost always designed by social scientists and directed toward improving thinking in the humanities and social studies, but the same can be accomplished with math and science courses. Properly taught university courses should teach a student critical thinking in addition to the disciplinary content of the course.

It is useful to ask why the scientific method--now recognized, in its guise of critical thinking, as so important to modern education that hundreds of critical thinking programs exist in thousands of schools across the nation--is so valuable for an individual to learn and practice. The reason is because the scientific method is the most powerful method ever invented by humans to obtain relevant and reliable knowledge about nature. Indeed, it is the only method humans have of discovering reliable knowledge (knowledge that has a high probability of being true). Another name for this type of knowledge is justified true belief (belief that is probably true because it has been obtained and justified by a reliable method). Nobel Prize-winner Sir Peter Medawar claimed that, "In terms of fulfillment of declared intentions, science is incomparably the most successful enterprise human beings have ever engaged upon." Other methods of gaining knowledge--such as those using revelation, authority, artistic and moral insight, philosophical speculation, hopeful and wishful thinking, and other subjective and authoritarian means--have historically resulted in irrelevant and unreliable knowledge, and they are no better today. These nonscientific methods of discovering knowledge, however, are more popular than scientific methods despite their repeated failures in obtaining reliable knowledge. There are many reasons for this, but two of the most important are that nonscientific methods are (1) more congenial to emotional and hopeful human nature, and (2) are easier to learn and practice than scientific methods. Despite these reasons, however, the value and power of possessing reliable knowledge--as contrasted with the usual unreliable, misleading, irrelevant, inaccurate, wishful, hopeful, intuitive, and speculative knowledge most humans contend with--have caused modern government, business, and education leaders to place the scientific endeavor in high regard, and caused them to promote teaching the scientific method and its popular manifestation: critical thinking.

Humans are conditioned from birth to follow authority figures and not to question their pronouncements. Such conditioning is done by parents and teachers using a wide variety of positive and negative reinforcement techniques. Most individuals reach adulthood in this conditioned form. The result of such conditioning is the antithesis of both scientific investigation and critical thinking: individuals lack both curiosity and the skills to perform independent inquiry to discover reliable knowledge. Individuals who think critically can think for themselves: they can identify problems, gather relevant information, analyze information in a proper way, and come to reliable conclusions by themselves, without relying on others to do this for them. This is also the goal of science education. Critical thinking allows one to face and comprehend objective reality by gaining reliable knowledge about the world. This, in turn, allows one to better earn a living, achieve success in life, better solve life's problems, and be reconciled to existence, mortality, and the universe. If a person is happier possessing reliable knowledge and living in objective reality, rather than living in ignorance and possessing false or unreliable beliefs, this is as good a reason as any for teaching and learning critical thinking.

Formal Critical Thinking Programs

There are two ways to teach critical thinking in the classroom. The first method, and the one we will find endorsed in this manual, is also the easiest, least time-consuming, and the least expensive. This method is to simply modify one's teaching and testing methods slightly to enhance critical thinking among one's students. This method is explained in the following two sections.

The second method--more difficult, time-consuming, and expensive--is briefly described now. This method makes use of formal critical thinking exercises, programs, and materials that have been prepared by specialists and can be purchased for immediate use by the teacher or instructor. These materials are the dominant means by which critical thinking is now being taught in primary and secondary education. For a single classroom, school, or school district, such formal critical thinking materials cost hundreds to thousands of dollars. The fact that critical thinking programs exist today is a sad commentary on the decline of education in the United States, for students apparently once learned critical thinking in our country without such materials.

Dozens of formal critical thinking programs exist. Here are just three that arrived unsolicited in my faculty mailbox:

First, the "CORT Thinking Program" by Dr. Edward de Bono, is a set of 60 "thinking lessons" that promise to "succeed in motivating students of all ages and abilities to: think--and develop creative solutions to problems--both inside and outside the classroom, improve the quantity and quality of their creative writing, and see themselves as active thinkers, and therefore able to hold a better self image of themselves and have confidence in their own ability to succeed."

Second, the "Strategies for Teaching Critical Thinking Across the Curriculum" from Education Testing Service consists of a two-phase professional development program for secondary-level educators that will enable them to "integrate the teaching of thinking skills into their instructional program, and train teachers in their schools and/or districts to do the same." Phase I teaches "introduction to thinking skills, concept formation, finding patterns, making inferences, formulating and testing hypotheses, and understanding and constructing meaning." Phase II teaches the teachers to train other teachers.

The third program, from Teacher's Press, asks "Are you concerned when American teenagers lack logical thinking skill, equate influence with tricks and bribery, are unable to

evaluate the reliability of data?" They have prepared high school course materials that actively address these concerns. For example, the description of their unit on "A Study of Logical Fallacies" states that, "Teaching critical thinking skills has long been accepted as a major goal of most teachers. Most probably say that they want to develop in their students a trusting, but questioning, world outlook. Most want students to actively investigate the world in a structured, scientific way--as opposed to blind acceptance of tradition, authority or folk wisdom."

Course Areas In Which to Emphasize Critical Thinking

The prior sections of this manual were written to describe critical thinking, to inform you about the pressing need to promote it among students, and to encourage you to make it part of your course curriculum and teaching method. Now you will learn where and how to do this in your own courses. Critical thinking can be presented or emphasized in all classroom areas: lecture, homework, term papers, and exams. We will examine each in turn. Some slight extra effort on the part of the instructor will be necessary, but the effort will be worthwhile because the results are so valuable for the student. Remember, as you teach critical thinking, teach also why it is worthwhile.

Critical thinking can be taught during:

- 1. Lectures** You may of course directly teach critical thinking principles to your students during lecture, but this is neither required nor advisable. Stay with your subject matter, but present this in such a way that students will be encouraged to think critically about it. This is accomplished during lecture by questioning the students in ways that require that they not only understand the material, but can analyze it and apply it to new situations.
- 2. Laboratories** Students inevitably practice critical thinking during laboratories in science class, because they are learning the scientific method.
- 3. Homework** Both traditional reading homework and special written problem sets or questions can be used to enhance critical thinking. Homework presents many opportunities to encourage critical thinking.
- 4. Quantitative Exercises** Mathematical exercises and quantitative word problems teach problem solving skills that can be used in everyday life. This obviously enhances critical thinking.
- 5. Term Papers** The best way to teach critical thinking is to require that students write. Writing forces students to organize their thoughts, contemplate their topic, evaluate their data in a logical fashion, and present their conclusions in a persuasive manner. Good writing is the epitome of good critical thinking.
- 6. Exams** Exam questions can be devised which promote critical thinking rather than rote memorization. This is true for both essay question exams and multiple-choice exams.

Your mission, if you decide to accept it, is to use one or more of the following classroom strategies or techniques to teach critical thinking in one or more of the above four course areas. You are encouraged to explore the possibilities and use as many as you wish. If you are already using some of these techniques, and many of you are, then you don't have to change a thing.

Critical Thinking Teaching Strategies and Classroom Techniques

Critical thinking cannot be taught by lecturing. Critical thinking is an active process, while, for most students, listening to lectures is a passive activity. The intellectual skills of critical thinking--analysis, synthesis, reflection, etc.--must be learned by actually performing them. Classroom instruction, homework, term papers, and exams, therefore, should emphasize active intellectual participation by the student.

Lectures: Enhancement of critical thinking can be accomplished during lecture by periodically stopping and asking students searching and thoughtful questions about the material you have just presented, and then wait an appropriate time for them to respond. Do not immediately answer such questions yourself; leave sufficient time for students to think about their answer before they state it. If you constantly answer such questions yourself, students will quickly realize this and not respond. Learn students' names as quickly as possible and ask the questions of specific students that you call upon by name. If an individual cannot answer a question, help them by simplifying the question and leading them through the thought process: ask what data are needed to answer the question, suggest how the data can be used to answer the question, and then have the student use this data in an appropriate way to come up with an answer.

You may, of course, ask simple questions that merely ask students to regurgitate factual information that you have just given them in lecture. Many students have trouble with these factual questions because they are not paying attention in class, they simply have never learned how to listen to a lecture and take mental and written notes, or they don't know how to review their notes and the textbook in preparation for an exam. Perhaps the most basic type of critical thinking is knowing how to listen to a lecture actively rather than passively; many students don't know how to do this because they were never taught it and they were able to get through the educational system to their present situation--your class--without having to practice it. (A good book to read or suggest to students that they read is *How to Speak, How to Listen* by Mortimer J. Adler.) It is probably wise to begin asking the factual type of question so that students will realize that they have to pay attention. However, the goal of critical thinking requires that you eventually ask questions that require students to think through a cause and effect or premise and conclusion type of argument. This obliges them to reason from data or information they now possess through the lecture to reach new conclusions or understanding about the topic. For example, in chemistry, after presenting information about chemical reactions, you could ask students to describe chemical reactions that occur to them or near them everyday by the combination of commonplace chemical materials. Ask them to explain what type of reaction it is (oxidation, reduction, etc.) using whatever knowledge they possess of the reactant materials and their new knowledge of chemical reactions.

Dr. Dennis Huston of Rice University, winner of numerous teaching awards, recommends asking such questions in class. He complains that we teach students to be mere receivers of information from the instructor, rather than getting them to talk about and trust their own thoughts about the subject matter. Huston states that thoughtful and searching questions often have uncertain and ambiguous answers; this is more true in his area of study (literature) than in math and science, but the concept is the same. Rather than condition students to value only what the instructor says, get them to think deeply about the topic and value what they think and feel. Teach so that students think their ideas matter. Ask them to make connections and recognize patterns. They will experience a responsibility for their own education and think about what they learn and read. Students will be involved with their own learning, will feel deeply about it, and learn to value and trust their own thoughts and ideas. These recommendations are a perfect application of promoting critical thinking.

After lecture but before the class ends, ask students to write one-minute papers on the most significant thing they learned in class today and what single thing they still feel confused about. Dr. Huston says

this is the single most important exercise you can do. You get immediate feedback about what the students are learning and what they still need to understand (technically, this is an application of what is called "classroom research" or "classroom assessment," the deliberate discovery of what and how much students are learning and of how you are teaching). He says it also improves their writing. In our present case, of course, this exercise improves critical thinking.

In class, encourage questions from students. Always respond positively to questions; never brush them off or belittle the questioner. Instead, praise the questioner (for example, say "Good question!" or "I bet a lot of you want to know that"). Questions from students mean they are thinking critically about what you are saying; encourage that thinking!

During lecture, bring in historical and philosophical information about math and science that enables students to understand that all scientific and mathematical knowledge was gained by someone practicing critical thinking in the past, sometimes by acts of great courage or tedious painstaking work in the face of seemingly insurmountable difficulties.

Laboratories: Many science courses have laboratories connected with them. Science laboratory exercises are all excellent for teaching critical thinking. The reasons should be obvious. Here, the student learns the scientific method by actually practicing it. This method of teaching critical thinking is so clear and obvious that it seems odd that critical thinking is not promoted more in primary and secondary education by simply beginning science instruction in the first grade and requiring that students take more science courses. You will have to decide for yourself why this isn't the case. Since laboratories automatically teach critical thinking to some degree, we will spend no more time on this topic.

Homework: Innumerable opportunities exist to promote critical thinking by homework assignments. For reading homework, Dr. William T. Daly recommends that you provide students the general questions you want answered before they begin reading, and insist that they organize their notes around these questions. Require that students transform the information and make it their own by requiring them to paraphrase, summarize, or outline all reading assignments. He suggests that you can grade their written efforts with oral quizzes that can be structured to require abstract conceptualization and graded as students speak, for most students will prepare carefully in order to avoid failing repeatedly in public. You may also, of course, collect, grade, and return their written efforts.

As stated above, getting students to write more is the best, and perhaps the easiest, way to enhance critical thinking (this is also the answer to the question, "How did students learn critical thinking before there were formal critical thinking exercises and modules?"). Writing forces students to organize their thoughts and think critically about the material. Ask students to write short papers about pertinent topics, review science articles, even paraphrase news articles and textbook chapters. These exercises can be as elaborate as you wish to make them. For example, Drs. Robin W. Tyser and William J. Cerbin (1991, *Bioscience*, v. 41, no. 1, p. 41-46, "Critical thinking exercises for introductory biology courses") propose the assignment of "science news exercises" designed to promote critical thinking. Students are asked to read a short science news article taken from the popular media (newspaper, science magazine, etc.), contemplate a list of take-home questions that include one or two hypothetical claims about the article, and a week later take a short quiz made up of questions selected from the list. The instructor prepares the questions and copies and distributes them and the news article to the students at biweekly intervals about six or seven times a semester. The authors state, "The ultimate goal of these exercises is to improve students ability to compose a concise, logically persuasive line of reasoning about why a claim should be either conditionally accepted or not accepted." They point out that their's and others' critical thinking exercises have been empirically demonstrated to develop science-related thinking skills in a course

without sacrificing the disciplinary content. For other examples of this type, please see W. R. Statkiewicz and R. D. Allen, 1983, "Practical exercises to develop critical thinking skills," *Journal of College Science Teaching*, vol. 12, p. 262-266, and M. P. Donovan and R. D. Allen, 1989, "Critical thinking questions for examinations and exercises," p. 13-16, in L. W. Crow, editor, *Enhancing Critical Thinking in the Sciences*, Society for College Science Teachers.

Quantitative Exercises: Problem solving is critical thinking; thus, courses such as mathematics, chemistry, and physics, that require the solution of various mathematical problems, automatically teach critical thinking to some extent just by following the traditional curriculum. When students are required to solve math problems, they are practicing critical thinking, whether they know it or not. Mathematics, chemistry, and physics problems belong, of course, to only a limited subset of critical thinking, but this subset is an important one. Indeed, all science courses--including those that do not traditionally require mathematical problem-solving skills at the introductory level, such as biology, geology, oceanography, astronomy, and environmental science--should begin to incorporate some mathematical problems in the curriculum. Asking students to solve math problems in a science gets them thinking about nature and reality in empirical and quantitative terms, key components of critical thinking.

One point, however, has been made by mathematics professor Dr. Robert H. DeVore. Do not, he says, make the mistake of believing that teaching mathematical manipulation alone will lead to critical thinking. Many arithmetical and mathematical problems and exercises will give the student the facility to manipulate numbers, but will not teach critical thinking. Dr. DeVore believes that mathematical word problems, that ask the student to approach the empirical world from a numerical or quantitative viewpoint, are essential to enhancing critical thinking. Indeed, he feels that math students who do not intend to take higher-level math courses should be educated in the context of word problems to the greatest extent possible. Obviously, students who are given math problems to solve in the sciences are essentially working on word problems, so the point is automatically made here.

Here are some examples of mathematical word problems prepared by Dr. DeVore (1-5) and Dr. John B. Scott (6-10) that were specifically devised to enhance critical thinking:

1. Show that to convert a Celsius temperature (C°) to a Fahrenheit temperature (F°), you can double C° , deduct 10% from the result, and add 32° .
2. Bob buys an item for X dollars. He raises the price 15% and sells to Tom. Tom lowers the price he paid by 15% and sells back to Bob. Bob's gain on the two transactions is \$2,812.50. What is the value of X?
3. Does $a(bc) = (ab)c$ on a calculator? First, use variables of your own choosing. Then, try using $a = 10-60$, $b = 10-60$, and $c = 1060$. On my calculator (Sharp EL-506A), the left side of the equation is 10-6 and the right side is 0.
4. Does $a+(b+c) = (a+b)+c$ on a calculator? Again, use variables of your own choosing. Now, try using $a = 1$, $b = 1020$, $c = -1020$. On my calculator, the left side of the equation is 1 and the right side is 0.
5. Is any law of algebra correct on a calculator?
6. Using a standard non-digital watch or clock, at what exact time in hours, minutes, and seconds are the hour and minute hands precisely coincident after 3:00 ?

7. A merchant has a square carpet priced at \$1.00 per square foot and a rectangular carpet, with length three times its width, priced at \$1.50 per square foot. The combined area of the carpets is 112 square feet, and the value of the rectangular carpet is \$8.00 more than the value of the square carpet. Find the dimensions of each carpet.
8. Two airports A and B are 400 miles apart, and B is due east of airport A. A plane flew from A to B in 2 hours and then returned to airport A in 2 1/2 hours. If the wind blew from due west with a constant velocity during the entire trip, find the speed of the the plane in still air and the speed of the wind.
9. A boat can travel 36 miles downstream in 1 hour and 48 minutes, but requires 4 hours for the return trip upstream. Assuming the boat and the stream have constanat velocities, find the velocity of the stream and the velocity of the boat in still water.
10. The periods of time required for two painters to paint one square yard of floor differ by one minute. Together, they can paint 27 square yards in one hour. How long does it take each painter to paint one square yard?

Term Papers: Term papers promote critical thinking among students by requiring that they acquire, synthesize, and logically analyze information, and that they then present this information and their conclusions in written form. Term papers are not traditionally required in math and science courses, although they may be and perhaps should be. We math and science instructors really don't require that students write very much and, when we do, don't require that they use correct spelling, punctuation, grammar, and syntax. At the very least, we should allow term papers as extra credit to give students a means to make up poor exam grades. Students who are doing poorly always ask if there is anything they can do to make up their grade; tell them from the first day that an optional term paper--of appropriate style, content, and length--will enable them to improve their grade in the course. Tell them that poor spelling, grammar, punctuation, syntax, and form will result in lesser credit. This technique can be used in any math or science course and is strongly recommended as a way to improve students' critical thinking skills. Perhaps as they research and write it, they will begin to think critically about the benefits of keeping up with lectures and studying for exams.

Examinations: Examinations should require that students write or, at least, think. For written exams, short- and long-answer essay questions are the obvious solution. For example, Dr. James T. Hunter, a biology professor, typically uses a few short-answer essay questions on each exam that test the ability of students to analyze information and draw conclusions. This commonly-used technique, by itself, helps to teach critical thinking. Some examples of these questions are as follows:

1. Using diagrams and/or descriptions, describe the synthesis of a protein beginning at the DNA level and ending with a finished protein.
2. Contrast the relative advantages and disadvantages of the light and electron microscopes.
3. Explain the importance of plasmids, biologically and in genetic engineering.
4. In your own words, give at least six ground rules for the collection of clinical specimens for microbiological studies.

But other possibilities exist. For example, Dr. Hunter modified some of his essay questions to challenge the student's critical thinking even more. He changed Question 4 above to the

following:

4. Lab technician Jim collects a culture from a patient on which the doctor previously operated. Jim carefully collects pus from a wound on the leg of the patient using a toothpick and then, seeing another wound on the face of the patient, washes the face wound with iodine and, using the same toothpick, collects serum from that wound. Jim drops the toothpick into a tube of nutrient broth, puts the name of the doctor on the broth culture tube, and takes it to the lab on the way home from work. List the mistakes Jim made.

In an experiment designed to further encourage critical thinking among students, Dr. Hunter included a take-home bonus question. These questions were chosen "to go beyond the lecture material and to force use of the book and lecture notes to arrive at and phrase a reasoned answer to a complicated question." This is an example of an essay question written specifically to enhance critical thinking. But please remember, almost any essay question, including those less elaborate than this, will serve to promote critical thinking. This is because writing, in itself, promotes critical thinking.

Finally, let us consider multiple-choice questions. Although these are constantly characterized as being inimical to the promulgation of critical thinking, the fact remains that they must often be used for exams. Large class sizes and student expectation of impartial grading are the two primary reasons to rely on multiple-choice questions. It is therefore encouraging to learn that multiple-choice questions can serve to enhance critical thinking if they are designed correctly. Let us examine some examples prepared by Dr. Steven D. Schafersman. First, as counter-examples, the following two questions *do not* promote critical thinking, because they rely solely on simple memorization:

1. The nucleus of an atom is composed of
 - a. protons and ions
 - b. neutrons and electrons
 - c. protons and electrons
 - d. isotopes and ions
 - e. neutrons and protons

2. The most abundant rock-forming mineral in the Earth's crust is
 - a. quartz
 - b. clay
 - c. feldspar
 - d. calcite
 - e. olivine

The following questions *do* promote critical thinking, because they ask the student to perform some reasoning along with the memorization:

3. If you drilled a well 8 kilometers deep and encountered rock of the mantle, your drilling rig would be
 - a. far offshore in the deep ocean
 - b. on the coastal plain near a continent's shoreline
 - c. on a mountain range
 - d. in a deep valley or basin near the center of a continent
 - e. nearshore in a subduction zone

4. Although 95% of the crust of the Earth is composed of either igneous or metamorphic rock, 75% of the exposed surface of the continental crust is sedimentary rock. This is because
- a. erosion of surface soil and rocks has produced a veneer of sediments over most of the Earth, and lithification of these sediments has produced sedimentary rock strata
 - b. the temperature of the Earth increases downward, leading to the creation of vast amounts of igneous and metamorphic rocks
 - c. oceanic crust, which covers about 70% of the Earth's surface, is largely composed of igneous rocks, such as basalt, which forms at oceanic ridges
 - d. constitute such a small percentage of the surface of the Earth that they contribute much less material to the surface than do physical and chemical precipitation of sediment
5. Of the following areas, the one least likely to be affected by a catastrophic mudflow is
- a. the Ozark Mountains of SW Missouri and NW Arkansas
 - b. the central Argentine Andes
 - c. the Cordilleras of Colombia
 - d. the Cascade Range of N California, Oregon, and Washington
 - e. the Texas Hill Country west of Austin
6. Which of the following is least likely to either trigger or enhance a mass-wasting process?
- a. an earthquake
 - b. a prolonged period of drought
 - c. marine erosion of a cliff face
 - d. rapid tectonic uplift
 - e. abundant precipitation in a brief period
7. Which of the following desert processes is most essential to the production of loess?
- a. deflation
 - b. saltation
 - c. rolling
 - d. oxidation
 - e. solution

The idea here is not profound. Many of you probably use this type of multiple-choice "think question" already. They simply ask that the student read the information provided in the question, examine the alternative answers, and perform one or more acts of reason in addition to any memorization necessary. Choosing among alternatives in multiple-choice exams, as in real life and any other intellectual pursuit, should involve more than memorization. Please design some of your multiple-choice questions in the future with this in mind.

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