Engineering Education, *77*(4), 222–227 (1987).

ON CREATING CREATIVE ENGINEERS

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The toughest problems facing our society—how to provide all our citizens with adequate and affordable food, housing, and medical care, efficient and economical public transportation, clean and safe energy—are not likely to be solved by easy or conventional means. If they could be, they would have been solved by now. To the extent that the problems are technological, creative engineers are needed to solve them. We—engineering professors—are in the business of producing engineers. It would seem our responsibility, and also in our best interest, to produce some creative ones—or least not to extinguish the sparks of creativity our students bring with them.

We are not doing too well at this, however. Despite all that has been written and said about problem solving and critical thinking, most engineering schools are still going about business as usual, relying on the traditional lecture-homework-quiz format of well defined problems and single correct answers. Unfortunately, while efficient, this format has never been shown to be effective at producing the critical, innovative thinking skills needed to solve difficult technological problems.

Nonetheless, as the pressure mounts to cram more and more information into each course, we find it increasingly hard to do anything but cover the syllabus. With the university reward system tilted overwhelming toward research, there are no incentives other than personal satisfaction for developing and testing new teaching methods."[2] So we continue to cover the syllabus, pretending that what we teach is the same as what our students learn.

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The work described in this article is based on four premises:

1) Techniques that have been found by psychologists and educational theorists to stimulate creative thought can be valuable adjuncts to traditional methods of engineering education.

2) To be effective, these techniques must be introduced throughout the curriculum and not relegated to elective courses on problem solving.

3) Methods intended to develop creativity and high-level thinking skills should not take too much class time. Much information must be covered in engineering courses (although perhaps not as much as we think), and rightly or wrongly, instructors will not adopt methods that prevent them from getting through the syllabus.

4) New methods should also not take too much of the instructor's time. Whatever its pedagogical soundness and potential benefits, a new method that takes a great deal of time and effort to implement will probably not be implemented. (Witness the fate of self-paced instruction.)

Space does not permit a review of approaches to developing creative problem solving skills. They have been described extensively elsewhere, and the bibliography on page 227 lists some of the key works.

The Generic Quiz

I attempted to put into practice several ideas for stimulating creativity in two classes I taught last year. The results proved to me that such exercises can produce some extremely interesting and thought-provoking results, and can be enjoyable to all concerned. Suitable groundwork must be laid, however, if the experience is to have any benefit.

My first excursion into these waters took place in a graduate course in chemical reactor design and analysis. For the third quiz of the semester I gave a five-week take-home exercise that asked students to make up and solve a final examination for the course. They were told that if they produced a straightforward "Given this and this, calculate that" quiz with no mistakes, they would receive a minimum passing grade. To receive more credit would require asking the hypothetical exam-takers to demonstrate the three higher-level thinking skills of Bloom's taxonomy: *analysis* (for example, determination of mechanisms, decomposition of systems, and derivation of relations beyond what could be found in texts or course notes); *synthesis* (e.g., application of techniques from other disciplines to reaction engineering problems, application of reaction engineering techniques to problems in other disciplines); and *evaluation* (e.g., assessing the value of a design or product or system rather than simply its technical correctness, and examination of environmental, safety, social, and ethical considerations in the context of process design and analysis).

The details of this exercise (which I termed the "generic quiz," since with almost no modification it can be applied to any subject at any level) have been described elsewhere.[4] The following is a brief summary.

In the first two or three weeks after getting the assignment, the students were extremely uncomfortable: they had been called on to play a new game and were unsure of the rules. (If you have ever tried anything innovative in class, you know that students hate not knowing the rules.) They were much more at ease following a homework assignment to make up (but not solve) a problem that involved some or all of the higher-level thinking skills. I collected their problems—which were uneven and in large part missed the point—and had them typed up and distributed in class with the authors' names removed. We discussed which thinking skills were evoked by each problem and how the problems could be improved. At that point, they began to get it, and their final examinations ranged from good to spectacular.[4]

After completing the assignment, the students almost unanimously reported finding the test hard, instructive, and enjoyable. Some of their comments suggest what the exercise did for them:

- Forces one to think deeper than just memorization, helps one to see interconnections between this course and others.
- 1) Forced a review of the course material (and beyond) in an integrated fashion. 2) Gave insight into what professors have been up against when making out all those tests I've taken over the years.
- I've always felt like the underdog when it comes to battles with tests, but this exercise made me feel strong. This type of test is one of the few that allows both the pragmatist and the theoretician to show their stuff.*

I concluded from this experience that devices like the generic quiz can indeed stimulate creativity and at the same time provide understanding of the course material beyond that normally achieved with the straight lecture-homework-test approach. A limited number of examples and opportunities to practice are essential to the success of exercises of this sort, and some student discomfort during their initial stages is unavoidable and—if kept within bounds—not necessarily undesirable.

> "If you have tried anything innovative in class, you know that students hate not knowing the rules."

Creativity Exercises in a Junior Course

A series of exercises I assigned in a junior-level course in fluid dynamics and heat transfer comprised three types:

1) Open-ended questions, where students were given a problem and, as part of the solution, were required to state what they needed to know to solve it and how they might go about obtaining the needed information;

2) Brainstorming exercises (e.g., think of as many ways as you can to accomplish a specified task);

3) "Make up a problem," along the lines of the generic quiz but on a much smaller scale.

Students were given roughly a week for each exercise and were told that they could work in pairs or individually. The exercises and the results obtained are summarized below.

EXERCISE 1

A toxic and potentially mutagenic substance (A) is contained in the wastewater from a chemical production plant. Batches of wastewater are dumped in a holding tank and treated with a biological agent that decomposes the hazardous substance into products generally acknowledged to be harmless. The decomposition rate is proportional to the concentration of A in the tank; that is,

$$r(\text{kg A reacting/liter-s}) = kC_A$$

where k is a constant and C_A(kg/liter) is the concentration of A in the tank. Once the concentration of A falls below a minimum value C_{min}, the contents of the tank are pumped into the river that flows past the plant. The tank processes a single batch of wastewater at a time.

You are the process engineer in charge of hazardous waste disposal. Your tasks are to calculate the minimum holding time from the moment the waste enters the tank to the moment the tank contents are discharged, and in general to review the procedure for feasibility and safety.

a) Define the quantities you would have to know to determine the minimum holding time. Then suggest ways to obtain values of these quantities.

b) Derive an expression for the minimum holding time in terms of the quantities specified in Part (a).

c) List as many possible defects in the waste disposal scheme as you can think of. For each, suggest how you would determine the likelihood of problems arising, safeguards that might be provided against their occurrence, and possible alternative procedures that might be preferable.

Responses to this question were

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* This student felt himself (with justification) to be an alien pragmatist in an academic world designed by and for theoreticians; sadly, the idea that practical skills might be valuable in engineering was new to him, although it is transparently obvious to anyone who has spent more than ten minutes in industry.

not particularly good. Most students realized that they would need values of parameters explicitly defined in the problem statement, but they had little idea how to get them. Few of them thought about unmentioned parameters like the initial concentration of A in the wastewater. Part (b) was straightforward and gave most students little trouble. In Part (c), the average number of possible system defects per student response was about four; the maximum was 10 and the total number of different ideas was 34. Few safeguarding procedures were suggested. Many students thought about leaks; others thought that the given rate law or rate constant or initial concentration might be incorrect; the biological agent might be ineffective or the wrong amount could be added; pipes might burst due to freezing, corrosion, or blockage of flow by scale, or sediment pressure could build up if the tank were closed and gases are released; side reactions might occur; and so on.

> …there was a wide variety of clever, ingenious, humorous, ribald, and altogether fantastic responses.”

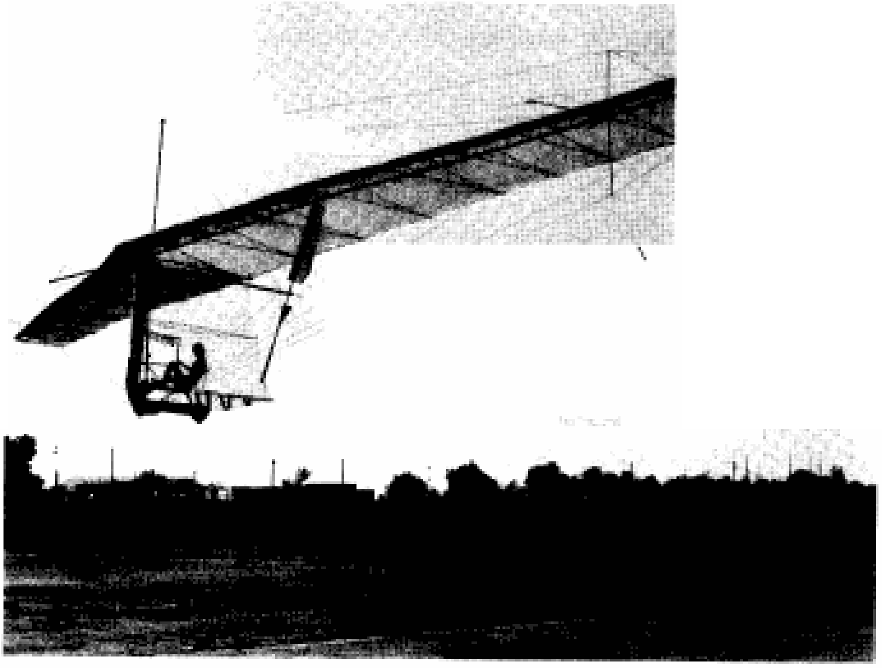
I compiled all the responses to Part (c) and distributed them to the class, telling them that in brainstorming all answers—including the less likely ones, such as an airplane crashing into the tank—count. I pointed out that seemingly absurd ideas often lead to good ones; the plane crash, for example, might suggest something less far-fetched crashing into the tank, like a truck or a crane. The average number of responses submitted in subsequent divergent thinking exercises climbed steadily as the semester progressed and students began to get the idea.

EXERCISE 2

You are faced with the task of measuring the volumetric flow rate of a liquid in a large pipeline. The liquid is in turbulent flow, and a flat velocity profile may be assumed (so that you need only measure the fluid velocity to determine the volumetric flow rate). The line is not equipped with a built-in flowmeter; however, there are taps to permit the injection or suspension of devices or sub-stances and the withdrawal of fluid samples. The pipeline is glass and the liquid is clear. Assume that any device you want to insert in the pipe can be made leak-proof if necessary, and that any technique you propose can be calibrated against known flow rates of the fluid.

Come up with as many ways as you can think of to perform the measurement that might have a chance of working. (Example: Insert a small salmon in the pipe, suspend a lure irresistible to salmon upstream of the insertion point, and time how long it takes the fish to traverse a measured section of the pipe.) You will get one point for every five techniques you think of (no fractional points awarded), up to a maximum of 10 points. Note, however: The techniques must be substantially different from one another to count. Giving me a pitot tube with 10 different manometer fluids, for example, will get you nowhere.

Thirty-one individuals and nine pairs submitted responses, for a total of 40 responses from 49 students. The average number of flow measurement techniques was 26; the high was *53*, the low was five. Some students found their way to reference books that listed different flowmeters, which was perfectly acceptable. Many were more inventive, and there was a wide variety of clever, ingenious, humorous, ribald, and altogether fantastic responses. Collectively, over 200 devices or methods were proposed; they are great fun to look at, but space does not permit their inclusion here.



EXERCISE 3

Make up (but don't solve) a problem involving fluid pressure drop and pump sizing calculations. The problem should involve some combination of analysis, synthesis, and evaluation. [The last three terms were explained in a short handout.]

Most of the problems submitted were routine, as would be expected for first attempts, but there were some surprisingly good efforts. Proposed problems involved sizing a pump for a nine-hole golf course sprinkling system; performing pressure drop calculations for the main synthesis unit of an underground drug laboratory; design calculations for a circulatory system to be used in open-heart surgery, including a continuous gravity feed system for anesthetic; a variety of mass and energy balance and hydrodynamic calculations for an aquarium-filter-pump system; and the design of an automatic control system for an acidic wastewater neutralization system.

EXERCISE 4

Your task this time is to devise as many ways as you can to measure the viscosity of a fluid. You will get one bonus point for each four ways you invent, up to a maximum of 10 points. Assume that any technique you use can be calibrated with fluids of known viscosity. A method that involves estimating the viscosity from measured data without using a calibration curve will earn double credit, if accompanied by a brief explanation of how the calculation would be done. A method that involves using a hamburger will also get double credit.

The following solutions will not receive credit this time: 1) Buy a viscometer; 2) Hire someone (or offer someone a hamburger) to measure the viscosity; 3) Ask someone who knows (human or deity); 4) Look it up in the Enquirer viscosity tables.

This creativity exercise resembles Exercise 2 superficially; however, the stipulation that double credit would be given to methods that did not require calibration encouraged the students to review every phenomenon studied in class that could be influenced by the viscosity of a fluid (e.g., settling velocity of a solid object, pressure drop in a packed bed or through an orifice, transition from laminar to turbulent pipe flow, etc.) and figure out how it could be turned into a viscosity measurement technique. Doing it without calibration meant that the relations governing the phenomena would have to be determined and converted into relations for the viscosity—in some cases, no small task. Giving double credit for solutions involving hamburgers (obviously, any noun could have been substituted) stimulated students to think of things they might never have thought of in a more conventional problem assignment.

EXERCISE 5

A hot gas stream leaves a process unit at 250°C and is discharged to the atmosphere. It is desired to improve the energy economy of the process by using this stream prior to discharging it.

a) One of the possible uses of the stream is to produce saturated steam in a boiler. What is an upper limit (bars) on the pressure at which the steam could be produced? Why would the actual pressure of the steam necessarily be lower?

b) Suppose steam is to be produced at a pressure 70 percent of the upper limit given in (a) by passing the hot gas through a coil immersed in liquid water. Outline the calculation of the required coil length, giving all of the equations and correlations you would use. List the quantities you would need to know to perform the calculation and how you would check them.

c) State as many other potential uses of the waste stream as you can think of. If there are conditions under which a use would be a bad idea or impossible, state what they are.

Part (a) is a trivial exercise in the use of the steam tables. Part (b) is a deliberately inadequate problem statement: one must assume that either the required amount of steam is known and that the flow rate of gas is adequate to generate it, or that it is desired to determine the maximum amount of steam that can be produced from the given gas flow rate. Most students took both flow rates as given, thereby overspecifying the problem. Few of them laid out a coherent solution procedure, and of those who did, most either never indicated how they would calculate the individual heat transfer coefficients, or simply said they would "measure or look them up."

By the time they reached this exercise, the students were becoming fairly adept at idea generation, and in their responses to Part (c) they submitted a wide variety of alternative uses of the waste stream, including using it to heat the plant, process units, boiler feedwater, food, a greenhouse, or the company sauna; drive a turbine, windmill, or compressor; melt snow, keep outside pipes or road surfaces from freezing; dry solid products, cars, clothes, hands, hair, or underarms; create vacuums, sterilize equipment, blow leaves or snow or glass, smother flames, fill hot air balloons, calibrate thermocouples, sculpt ice, burn intruders on the plant grounds, kill insects, defoliate jungles, and commit suicide.

Student Performance

Most students tried most or all of the exercises, and their performance levels generally increased as the term went on. There did not seem to be a strong correlation between performance on the exercises and performance on conventional homework and tests: some students did very well or poorly on both, others did well on one and fair-to-mediocre on the other. Not surprisingly, they did best on the types of exercises in which they had the most practice: extremely well on the divergent thinking (brainstorming) exercises, of which there were four; less well on the open-ended questions; and poorly on the problem formulation exercises, of which there was only one.

In their course evaluations, students were almost uniformly positive about the exercises, with most indicating that they both learned from them and enjoyed them. From my point of view, the exercises were highly successful. I could see a growth in the divergent thinking ability of many students; their responses provided me (and them) with excellent material for initiating class discussions; and it was all done without taking a great deal of class time. Perhaps more importantly, the exercises allowed several of the more creative students to discover that they enjoy and are good at divergent thinking, and that they can use this ability to solve difficult problems. While this discovery does not guarantee that they will go on to perform great feats of creativity in science and engineering, it is surely a good first step toward that end.

Summary and Recommendations

The familiar lecture-homework-quiz format that constitutes the basis of most engineering courses is an efficient way to present a lot of information in a limited time. Our job as engineering educators, however, should not be merely to impart facts but to prepare students to solve problems. If we are doing our job well, our graduates should be equipped to define problems and devise strategies for attacking them, determine the information they need to implement these strategies, figure out where or how to get the information, and evaluate the implications of their solutions beyond their immediate technical context.

If we are to develop and nurture critical and creative problem-solving skills in our students, we must provide periodic opportunities to exercise these skills, a classroom atmosphere that lends itself to such exercises, and recognition and encouragement of those who display talent along these lines. Moreover, we must do so within our regularly scheduled engineering courses, so that these thinking and problem-solving skills come to be thought of as routinely applied tools of the engineer’s trade.

Many different creativity exercises have been suggested in references cited in the bibliography and elsewhere in the literature. These exercises are of several types:

1) Questions that call for ideational fluency (where what counts is the quantity of possible solutions, not their quality), flexibility (variety of solutions), and originality;

2) Questions that are poorly defined and open-ended, rather than well defined and convergent;

3) Questions that require synthesis of material that transcends course or disciplinary boundaries;

4) Questions that require evaluation, in which technical decisions must be tempered with social and ethical considerations; and

5) Questions that call for problem finding and definition in addition to, or instead of, problem solving.

Clearly, the number of such exercises that can be assigned in a regular engineering course is limited, and the scope and nature of the exercises must depend on the level and size of the class. (One would not think of giving the generic quiz, for example, to a class of 150 sophomores. Who would grade them?) However, giving a few such exercises in the course of a semester, as was done in the fluid mechanics course mentioned in this article, can have the desired effect without taking excessive class time away from covering traditional course material.

As beneficial as such exercises may be, simply providing them does not guarantee they will improve students' skills, any more than providing information in a lecture guarantees that anything will be learned. Teachers must create conditions that are conducive to receiving the material being presented. There are obvious ways to do this, such as encouraging questions and innovative suggestions, and responding positively when they are forthcoming. Other approaches, such as small-group brainstorming activities, can be used effectively to stimulate the free generation of ideas in a relatively safe setting.

An instructor attempting to get students to do things in unfamiliar ways must anticipate resistance, and should not be discouraged by initial results, which are likely to be dismal. Some preparation, in which the class is told the purpose and relevance of the new approach and given some (but not too many or too detailed) illustrations of what is being called for, is essential. Repetition is also necessary, since students (like everyone else) tend to resist new ideas, and very few will "get it" the first time.

Finally, instructors who assign exercises in creative thinking should be on the lookout for students who seem to have talent along these lines. Creative thinkers see things differently from most people. Since being different is not tolerated very well in our social and educational systems—particularly in childhood and adolescence—creative people may attempt to divert their individuality into what may seem more acceptable forms: disappearing into the crowd, or appearing bored or indifferent. In consequence, the creatively talented may well be found among the population not usually considered academically gifted. They are often erratic in their class performance and reluctant to contribute their ideas, which are generally not welcomed in traditional class settings. When given the chance to use their gifts for innovative thinking, however, these students may discover, perhaps for the first time, the potentially great value in what they can do. This knowledge may be all they need to put their talents to use in school and career.

It is also likely that among our academically gifted students are some with great untapped creative potential—students who learned early that you win in the school game by coming up with the right answer (i.e., the one the instructor had in mind), and you lose by pursuing innovative tangents. Being clever, these students catch on quickly, and early in their lives put the right halves of their brains on hold. They are the ones most likely to solve the most difficult problems, the ones with both the creativity to come up with the innovative ideas and the analytical ability to make them work. Giving just a few of them the key to valuing and using *all* their gifts may be the most significant contribution we can make to our society as teachers.

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