CREATIVITY IN ENGINEERING EDUCATION

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> ***Unless man can make new and original adaptations to his environment as rapidly as his science can change the environment, our culture will perish.***
> ***Carl R. Rogers***

There has been much discussion in recent years on the need for creative engineers in American industry and the associated need for engineering schools to foster creative thinking ability in their students [1-5]. The first problem one encounters when thinking about how these needs might be addressed is that while creativity has been exhaustively studied [6-11], it has never been satisfactorily defined. There is general agreement, however, that creativity (whatever it is) involves the ability to put things (words, concepts, methods, devices) together in novel ways. Moreover, at least some types of creative ability are thought to involve skill at *divergent production*—generation of many possible solutions to a given problem—as opposed to *convergent production*, or generation of "the right answer" [7,8].

Academic excellence (at least in engineering) is synonymous with skill at convergent production, since engineering education (unlike engineering practice and life in general) normally involves only problems with single correct answers. On the other hand, both convergent and divergent production are required to solve serious technological problems. The purely convergent thinker is not likely to come up with the innovative solution required when conventional approaches fail, while the purely divergent thinker will generate a great many innovative ideas but may lack both the analytical ability to carry them through to their final form and the evaluative ability to discriminate between good and bad solutions. If we as engineering educators cannot find enough individuals who combine these abilities, at the very least we should be turning out some who excel at one and some who excel at the other. To do this, we must provide instruction and practice in *both* modes of thinking.

In this respect we are failing abysmally. In the educational experience we provide for our students, from the first grade through the last graduate course, never (well, hardly ever) are words breathed to the following effects:

- **Some problems do not have unique solutions.**
- **Some problems may not have solutions at all.**
- **Problems in life, unlike problems in school, do not come packaged with the precise amount of information needed to solve them—some are overdefined, and most are underdefined.**
- **Problems in life, unlike problems in school, are open-ended: there is no single correct solution and any realistic answer invariably begins with, "It depends. . . ."**
- **The more possible solutions you think of for a problem, the more likely you are to come up with the best solution.**
- **Sometimes a solution that at first sounds foolish is the best solution.**
- **To be wrong is not necessarily to fail.**

If we are to produce engineers who can solve society's most pressing technological problems we must somehow convey these messages in our instruction.

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We must provide our students with opportunities to exercise and augment their natural creative abilities and we must create classroom environments that make these exercises effective. The balance of this paper suggests methods for achieving these objectives.

CREATIVITY EXERCISES

> *The need to be right all the time is the biggest bar there is to new ideas. It is better to have enough ideas for some of them to be wrong than to be always right by having no ideas at all.*
>
> *Edward de Bono*

> *Every really new idea looks crazy at first.*
>
> *Abraham H. Maslow*

Many techniques have been suggested for exercising creativity and developing problem-solving skills in the classroom. (See, for example, the articles in Lubkin [12], especially that by Woods *et al.*, and Costa [13].) In every course some open-ended and underdefined problems should be assigned, and more information than is needed should be provided for problems with unique solutions. Problems should also be assigned which call for the generation of possible alternative solutions, and when the solutions are evaluated credit should be given for fluency (number of solutions generated), flexibility (variety of approaches adopted), and originality.

If the generation of possible solutions is to be done effectively, it is essential that the critical facility be suspended in the initial stages of the process. The problem-solver must feel free to advance any idea that occurs, regardless of its apparent practicality or lack of it. A number of techniques have been used successfully to facilitate the uncritical generation of ideas. Following are several that have been found particularly effective in industrial settings:

1. ***Alex F. Osborn's Checklist for New Ideas*** **(cited in Arnold [14]). A series of questions is used to stimulate new ways of thinking about a process, plan, or device.**

    - **Adapt? (Are there new ways to use this as is? Other uses if modified?)**
    - **Modify? (New twist? Change meaning, color, motion, sound, odor, form, shape? Other changes?)**
    - **Magnify? (What to add? More time? Greater frequency? Stronger? Higher? Longer? Thicker? Extra value? New ingredient? Duplicate? Multiply? Exaggerate?)**
    - **Minify? (What to subtract? Smaller? Condensed? Lower? Shorter? Lighter? Omit? Streamline? Split up? Understate?)**
    - **Substitute? (Who else instead? What else instead? Other ingredient? Other material? Other process? Other power source? Other place? Other approach? Other tone of voice?)**
    - **Rearrange? (Interchange components? Other pattern? Other layout? Other sequence? Transpose cause and effect? Change pace? Change schedule?)**
    - **Reverse? (Transpose positive and negative? How about opposites? Turn it backward? Upside down? Reverse roles? Turn tables?)**
    - **Combine? (Blend? Alloy? Assortment? Ensemble? Combine units? Combine purposes? Combine appeals? Combine ideas?)**

2. ***Attribute Listing,*** **proposed by Robert Crawford (cited in Arnold [14]). List attributes or specifications of the entity to be improved, and systematically try modifications or variations. Example: a screwdriver—(1) round, steel shank; (2) wooden handle riveted to it; (3) wedge-shaped end for engaging slot in screw; (4) manually operated; (5) torque provided by twisting. Then try changing each one, separately and in combinations, and see what you come up with.**

3. ***Morphological Analysis,*** **proposed by Fritz Zwicky (cited in Arnold [14]). Set up axes for principal attributes of the entity, with entries for each variable. Example: devise a mode of transportation for a specific application. One axis would be the form of conveyance (cart, chair, sling, bed, capsule, . . .), another is the medium in or on which the transportation occurs (air, water, oil, rollers, rails, . . .), another is the power source (internal combustion, compressed air, electricity, steam, magnetic fields, cable, belt, atomic power, . . .). Then try to come up with an example of each possible combination of variables (** ***i.e.,*** **every point on the grid formed in the space of the axes).**

4. ***Random stimulation,*** **one of the techniques suggested by Edward de Bono [15] under the general framework of "lateral thinking," in which something arbitrary is selected and an attempt is made to apply it to the problem at hand. Use a dictionary to provide a random word. Pick a book or journal off a shelf, choose any article or chapter, and apply the information to the given problem. Pick the nearest red object.**

    Making students combine two apparently unrelated concepts in this manner forces them to think about their problem in new ways, which is the object of the exercise. In a recent junior-level class on fluid dynamics and heat transfer [5] students were assigned to think of as many ways as they could to measure the viscosity of a fluid. Extra credit was given for any method that involved the

use of a hamburger. (An instructor who dislikes whimsy could use a more serious sounding noun—it makes no difference.) The results were enjoyable: students measured the settling velocity of a hamburger in the fluid; poured the fluid over the hamburger like ketchup and measured its spreading rate; covered a flat surface with the fluid and skipped the hamburger across it like a stone; offered a hamburger to someone who owned a viscometer; and came up with a number of other ideas that (with some stretching of the imagination) could lead to viable viscosity measurement methods.

5. ***Brainstorming,*** **formally developed by Alex F. Osborn. A problem is posed and a group session is held in which ideas are proposed and recorded but not evaluated critically, and then in a subsequent session the ideas are evaluated and the less promising ones are culled out. The idea generation phase can be completely unstructured or one of the preceding four techniques can be used as the basis of the exercise. Any idea, no matter how far-fetched, is fair game.**

    Several brainstorming exercises were used recently in the junior fluids/heat transfer course cited previously [5]. One asked students to come up with methods of measuring the velocity of a fluid in a pipe when no conventional flowmeter is available (several students reached the upper limit of 50 distinct solutions); another described a hazardous waste treatment method and called on the students to identify as many potential flaws in the method as possible; a third requested them to think of as many uses as they could for a hot stack gas; and a fourth was the viscosity measurement exercise.

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Such exercises serve several useful purposes: they encourage and reward creative thinking; they force students to look at the subjects they are studying from different perspectives, which leads to deeper understanding; they provide excellent points for class discussion; and they are enjoyable to both the students and the instructor. In addition, if they are done in class they are remarkably effective at getting all of the students involved as opposed to the few who are normally willing to ask and answer questions in public. Which technique is used is immaterial: the idea is to introduce novel ways of looking at problems—to force thinking patterns out of their well-worn grooves—and all of these methods achieve this objective.

A word of caution, however. Exercises of these types seem like games when they are first introduced and they can easily be dismissed as trivial or frivolous by faculty colleagues and by the students themselves. Woods and Crowe, for example, report that students introduced to brainstorming in a freshman design course felt the experience was "mickey mouse" and not useful [16]. It should be impressed on the students that whatever these methods may look like, they are used extensively in industry to generate ideas for new products, cost reductions, and solutions to difficult problems.

Once the ideas have been generated and collected, the next phase of the process is to bring back the critical facility and select the solutions that have the greatest promise of working. Here we are on much more familiar ground where the convergent thinking skills that the students are used to exercising can once again be called into play. At the conclusion of the process, however, the students should be reminded that the more innovative of their eventual solutions probably would not have emerged from a conventional approach.

Where in the curriculum should this type of exercise be introduced? One possibility is to present an elective course on problem-solving methods; however, I would argue that this is not a good way to go. For one thing, these classes only reach a fraction of the population that could benefit from them. For another, they convey the impression that creative problem-solving methods are in a separate category from regular engineering analysis: you use them in this course, but for normal engineering problems you go back to business as usual. Instead, the methods should be integrated as thoroughly as possible into the regular curriculum. Open-ended and divergent problems can be assigned to individuals or to small groups as in-class exercises, homework, or take-home quizzes [4, 5]. Assignments to groups of two or three are particularly effective; students tend to enjoy them, competing with one another at coming up with outrageous ideas, and they also discover the synergistic effects of group interactions on the generation of problem solutions.

Training should be provided in asking questions, not just answering them, especially in advanced undergraduate and graduate courses. Several examples of problem-defining exercises have been presented recently [4, 5]. In one instance [4], students in a graduate course in chemical reaction engineering were asked to make up and solve a final examination for the course. They were told that a straightforward "given this, calculate that" examination would earn only a minimum passing grade, and to get more credit they would have to include questions that called for analysis beyond that contained in the text, synthesis

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of material from other subject areas, and subjective evaluation.

The results of this exercise ranged from acceptable to spectacular. Excellent questions were formulated covering every aspect of chemical reaction engineering and incorporating elements from chemistry, biotechnology, a variety of other scientific and engineering disciplines, behavioral psychology, and several topics that defy classification. The students almost unanimously reported finding the exercise instructive and enjoyable and many of them indicated satisfaction at discovering abilities in themselves that they had never valued or even knew they had. The exercise has subsequently been repeated twice with equally good results.

Two factors are necessary for exercises of all types listed above to be effective: preparation and repetition. The class should initially be given some background on what the exercises are supposed to accomplish. What is divergent thinking, for example, and why is it important? What are synthesis and evaluation? What is the point of underdefining homework problems? Illustrative solutions should be presented to give the students an idea of what they are being asked for but not to an extent that the students can use them as detailed models. This preparation can be accomplished with a handout preceding the first problem assignment plus about fifteen minutes of explanation in class.

The need for repetition is critical. *Each new type of exercise should be assigned at least twice and ideally three times.* In their responses to the first assignment the students will almost invariably miss the point and try to convert the exercise into something they know how to do, or they will avoid it altogether out of fear of getting it wrong. The second time they will begin to take the assignment seriously but will generally do a mediocre job. By the third time most of them will start catching on. At this point it is time to move on to something different.

A useful method to accelerate adaptation to a new approach is to collect representative samples of the responses to the first assignment, reproduce them without attribution, distribute them to the class, and discuss them. The discussion should bring out the strong points of the responses and provide ideas for how they could be improved. When this is done the improvement in responses to subsequent assignments is usually dramatic.

CREATING AN ATMOSPHERE HOSPITABLE TO CREATIVITY

> ***What is then the correct way of teaching people to be, e.g., engineers? It is quite clear that we must teach them to be creative persons, at least in the sense of being able to confront novelty, to improvise. They must not be afraid of change but rather must be able to be comfortable with change and novelty, and if possible (because best of all) even to be able to enjoy novelty and change.***
>
> ***Abraham H. Maslow***

Perhaps even more important than providing exercises in creativity is making students feel secure about participating in them. Most of us learn early that being wrong is unacceptable and looking foolish is even worse, and these lessons are reinforced throughout our lives. Unfortunately teachers are frequently the worst offenders in creating these fears, and the child who is humiliated for asking a "stupid" question or coming up with a "ridiculous" idea or offering an "obviously wrong" solution will wait a long time before sticking his or her neck out again. If we are indeed to produce creative engineers, we should be offering classes in which the risk-taking usually needed to solve real problems is encouraged.

No matter how secure we professors are in our knowledge, there is in most of us the fear of finally being caught, of being asked something we think we're supposed to know but in fact don't. Many of us consequently have a tendency to discourage questions, although usually not intentionally. Also, since most or all of our teaching is based on the precisely defined, closed-ended problem with one and only one correct solution, we tend to get annoyed when a student produces a correct solution other than the one we had in mind—it confuses the grading terribly. When students come up with unanticipated ideas, our impulse is to prove them wrong—both the ideas and the students.

Eventually, the students get the message. At best they will just stop asking hard questions and offering ideas that might be thought wrong or foolish and will instead concentrate simply on figuring out what we want and then giving it to us. In the worst case—when they find no outlet in the educational system for their creative impulses—they will turn those impulses off, perhaps for the rest of their careers and lives, to their own detriment and society's loss.

Several things can be done to create a relatively safe atmosphere for questioning and idea generation:

- ***Encourage and applaud questioning. Asking a question in class is taking a risk; if we are to encourage risk-taking in our students this is a good place to begin. Even when a question seems "stupid," try if at all possible to find merit in it, even if it means reinterpreting it or extending it to something that the questioner undoubtedly never dreamed of.***

- ***When you ask students for suggestions, give them time to think of answers, don't criticize incorrect solutions, and don't automatically stop asking when you get the answer you're looking for.***

- ***If you really want student responses, an almost sure way to get them is to divide the class into small groups (3 or 4 in a group) and tell the students to formulate questions or ideas among themselves; then call on a member of each group to write down the things they came up with. Most students feel safe talking, questioning, and floating ideas in a small group of their peers and the relative freedom they feel in this setting frequently carries over to subsequent full-class discussions. This technique is particularly useful for large classes, in which student involvement is almost impossible to get by conventional means.***

- ***Offer leading questions as focal points for brainstorming sessions. The questions can be designed to improve understanding of the course material, such as "Which steps are unclear in this derivation?" "What have I assumed that I didn't specifically tell you?" "What more would you need to know to really understand how this device functions?" They can also be used to stimulate thought and discussion about applications and extensions of the material. "How could you measure this quantity?" "What possible applications might there be of the result we just proved?" "Think of as many things as you can that could possibly go wrong here and what might be done to correct them (or prevent them)."***

- ***Be on the lookout for solutions, correct and incorrect, that show clear signs of creativity, and take care not to discourage the imaginative impulses that gave rise to them. Reward innovation. Reward ideas drawn from fields other than that of the course in progress.***

- ***When innovative solutions, correct and incorrect, are forthcoming, make them and your positive response to them public so others in the class get the idea.***

- ***Provide case histories of problem solutions, especially creative ones. Show how incomprehensible the process seems when only the final solution is presented; then show the steps, including false starts and blind alleys, that led to that result. In Torrance's phrase, "Dispel the sense of awe of masterpieces." [17]***

IDENTIFYING THE CREATIVELY GIFTED

> ***The sad fact is that teachers generally do not prefer the more creative students. Furthermore, they do not have much confidence in the future success of the more creative students.***
>
> ***J.P. Guilford***

The creatively gifted seem to resist being classified, which is exactly what one would expect of people who think in unique ways. A number of instruments have been devised that are supposed to measure creative potential but no general agreement exists regarding their validity or reliability. However, studies suggest that certain traits are characteristic of creative individuals, including independence, inexhaustible curiosity, tolerance of ambiguity in problem definitions, willingness to take risks, persistence in pursuit of problem solutions, and the patience to allow the solutions to take shape in their own time.

The problem is that these characteristics are difficult for course instructors to spot, since they don't show up in normal classroom activities. Other characteristics of some creative individuals are more easily recognizable but are unfortunately apt to be viewed in a negative light. Reid [2] speaks of creative students whose course performance is highly erratic—very good grades in some courses, very poor ones in others. Other studies of creative individuals also refer to the possible presence of such personality traits as self-confidence bordering on arrogance, introversion bordering on misanthropy, and indifference bordering on hostility directed at anything that diverts the individual from his or her immediate areas of interest.

The oddball makes us uncomfortable. The student in the next-to-last row, chin in hand, looking bored or apparently sleeping, who suddenly pipes up in the middle of a phrase with the killer question that zeroes in on the flaw in our logic—our unstated assumptions, the exception we never thought of—is not someone we welcome in our classes with gladness in our hearts. Those of us without high degrees of self-confidence don't particularly want to see him coming, and if there is a way to put him down or shut him up we are tempted to grab it. Failing that, we go to the delay game: "Good question, but we really don't have time for it now. I'll get back to you later." That is often the last anyone hears of it unless our nemesis is pushy enough to come back with it.

Obnoxious behavior may in fact be the negative sign we take it to be. However, it could also be an indicator of the type of thinking ability needed to solve problems that defy conventional solution. There are times when we are in unique positions to encourage or stifle creative individuals in our program, such as when we advise students, assign grades in courses or projects, and evaluate applications for graduate school. On such occasions we might look twice at the individuals who display the traits we have been discussing, hunt for evidence of a creative spark in the erratic or socially unacceptable behavior with which they often confront the world, and attempt to convince them that they have something unique and critically important to contribute.

It is unfortunate, but true, that many creatively gifted students have never been told they are gifted; they only know that they are different and that their differences are socially unacceptable. It may take nothing more than recognition from a single professor to set them on the path to the productive use of their gifts for the rest of their careers and lives.

REFERENCES

1. Felder, R. M., "Does Engineering Education Have Anything to Do with Either One?" R. J. Reynolds Industries Award Distinguished Lecture Series, N.C. State University, Raleigh, NC, October 1982. A condensed version of this monograph appears in *Engineering Education,* **75,** November 1984, p. 95.
2. Reid, R. P., "Creativity and Challenges in Chemical Engineering," Olaf Hougen Lectures in Chemical Engineering, University of Wisconsin, Madison (1982). See also *Chem. Eng. Progr.*, 77(6),23(1981).
3. Prausnitz, J. M., "Toward Encouraging Creativity in Students," *Chem Eng. Education,* Winter 1985, p. 22.
4. Felder, R. M., "The Generic Quiz: A Device to Stimulate Creativity and Higher-Level Thinking Skills," *Chem. Eng. Education,* Fall 1985, p. 176.
5. Felder, R. M., "On Creating Creative Engineers," *Eng. Education,* January 1987, p. 222.
6. Barron, F., and D. M. Harrington, "Creativity, Intelligence, and Personality," *Ann. Rev. Psych.*, **32,** 439 (1981).
7. Guilford, J. P., *The Nature of Human Intelligence,* New York, McGraw-Hill (1967).
8. Guilford, J. P., *Way Beyond the IQ: Guide to Improving Intelligence and Creativity,* Buffalo, Creative Education Foundation (1977).
9. Rogers, C. R., "Toward a Theory of Creativity," in S. J. Parnes and H. F. Harding, eds., *A Source Book for Creative Thinking,* New York, Charles Scribner's Sons (1962).
10. Stein, M. I., "Creativity as an Intra- and Inter-personal Process," in S. J. Parnes and H. F. Harding, eds., *A Source Book for Creative Thinking,* New York, Charles Scribner's Sons (1962).
11. Maslow, A. H., *The Farther Reaches of Human Nature,* New York, Viking Press (1971).
12. Lubkin, J. L., Ed., *The Teaching of Elementary Problem Solving in Engineering and Related Fields,* Washington, American Society for Engineering Education (1980).
13. Costa, A. L., Ed., *Developing Minds: A Resource Book for Teaching Thinking,* Alexandria, VA, Association for Supervision and Curriculum Development (1985).
14. Arnold, J. E., "Useful Creative Techniques," in S. J. Parnes and H. F. Harding, eds., *A Source Book for Creative Thinking,* New York, Charles Scribner's Sons (1962).
15. de Bono, E., *Lateral Thinking,* New York, Harper and Row, 1970.
16. Woods, D. R., and C. M. Crowe, "Characteristics of Engineering Students in Their First Two Years," *Engineering Education,* February 1984, p. 289.
17. Torrance, E. P., "Creative Thinking through School Experiences," in S. J. Parnes and H. F. Harding, eds., *A Source Book for Creative Thinking,* New York, Charles Scribner's Sons (1962). ☐

ChE book reviews

HEAT AND MASS TRANSFER IN REFRIGERATION AND CRYOGENICS

By J. Bougard and N. Afgan, Editors
Hemisphere Publishing Corp., 79 Madison Ave., New York, NY 10016; 665 pages, $165.00 (1987)

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This book is a compilation of papers presented at an International Symposium organized by the International Centre for Heat and Mass Transfer in Dubrovnik, Yugoslavia, on September 1 to 5, 1986. The forty-three papers included in this proceedings address three areas of concern to specialists working at low temperatures, namely: thermodynamic and thermophysical properties; heat and mass transfer in refrigeration and at low temperatures; and thermal insulation. As is typical of most meeting proceedings, the quality and the infomation provided in the papers vary rather widely. A few of the more interesting papers will be noted.

A good review of the thermodynamic analyses that need to be made for refrigeration cycles is presented in one of the plenary papers. After classifying refrigeration cycles into three general types, the author utilizes energy and exergy balances to show the effect of heat and mass transfer irreversibilities in these cycles. He notes that a ratio of exergy loss to heat transfer of 1-3 percent can, with the inefficiencies of compression equipment, result in an energy dissipation that is equivalent to 5-20 percent of the overall heat flux. Guidelines for reducing these losses are suggested.

In the heat and mass transfer area there are a number of good papers providing new experimental studies for pool boiling and film boiling heat transfer. The heat transfer and thermodynamic studies made with a number of less used but more environmentally acceptable refrigerants will be of particular interest to designers looking for alternative refrigerants to the commonly used R11 and R12. Unfortunately, considerable more work must be performed before good choices can be made between these alternative refrigerant mixtures. Another area of heat and mass transfer receiving considerable emphasis was that of freezing soil. One of the papers provides a good experimental and numerical analysis of the coupling of heat and mass transfer in partially saturated frozen soil. The model developed in this study provides a good correla-