Open-Ended Problems: A Future Chemical Engineering Education Approach. J. Patrick Abulencia and Louis Theodore.

Part I

INTRODUCTION TO THE OPEN-ENDED PROBLEM APPROACH

This part is a stand-alone portion of the book, which serves the sole purpose of introducing the reader to open-ended problems and the open-ended problem approach.

The reader is constantly reminded of the need for change in the chemical engineering curriculum and, there is a need to change. The key word in the new chemical engineering curriculum will be *innovation*. It *must* be innovation if the profession is to survive. Presenting problems with "discrete" solutions thwarts the preparation of students by constraining their vitality, energy, and intellectual capabilities, and will minimize their impact on the future marketplace. Thus, failure to develop the innovative skills of future chemical engineers will adversely affect their careers. Bottom line: creativity, imagination, and (once again) innovation will be a requisite for success in the future.

Finally, the reader should note that a good part of the material presented in this Part was adapted from the earlier work by Theodore titled *Chemical Engineering: The Essential Reference*, Chapter 30 Open-Ended Problems, McGraw-Hill, New York City, NY, 2014. [1]

Overview

The phrase for success at the turn of the 20^{th} century was: work hard and you will succeed. What was heard during the careers of both authors as educators and practitioners was the phrase: work intelligently and you will succeed. However, the key phrase for the 21^{st} century is: be *innovative* and you will succeed. This will be the theme for the engineers and scientists of tomorrow; and, more than any other profession, it will become the key to success for future chemical engineers. For success to follow, the education of chemical engineers, in terms of the curriculum, will have to change if they are to succeed.

As noted earlier, the key word in the new chemical engineering curriculum will be *innovation*. It *must* be innovation if the profession is to survive. It will require more than possessing traditional problem-solving skills in order for the chemical engineering workforce to be appropriately educated. The authors have always advocated that one of the most important jobs of an educator is to anticipate the future.

Career paths in chemical engineering are now undergoing a change—a drastic change in the authors' opinion. The days of the need for massive numbers of chemical engineers required to size pumps, design heat exchangers, predict the performance of multi-component distillations columns is now a distinct memory. Handbook solutions are being replaced with creative, innovative action; hard work is being replaced by the need to understand software, etc. The conversion process will take time; educating and cultivating this intellectual approval for the new breed of engineers will not come overnight. But the time to start is NOW.

In terms of introduction, the cliché of the creative individual has unfortunately been aptly described throughout history- the Einsteinian wild hair, being locked in a room for days at a time, mumbling to one's self, eating sporadically, lost in a fog of conflicting thoughts, not paying attention to one's hygiene, working diligently until that times when the "light goes on" moment of discovery, etc. This chapter will provide (among other things) specific suggestions on how to develop and improve one's critical thinking abilities. [2]

Engineering is one of the noblest of professions, and the authors are extremely proud to be part of it. They are fortunate to have served as chemical engineering educators during their careers. A good part of this effort was directed to improving critical thinking skills of students in recent years. Check any engineering school's web-site and locate its mission statement. Many of these will carry the phrase "fosters creativity and innovation" among its students. But do they really? The authors hope so. But then again, how does one teach it? [2]

As a chemical engineering educator, one is required to teach traditional basic scientific and technical principles in courses like thermodynamics, heat transfer, reaction kinetics, etc., but, along with the lectures, one should include an emphasis on creativity, problem solving and *failure(s).* These three terms are definitely interrelated. Finding solutions to problems is a creative activity. Failure comes into play since there are often solutions with high uncertainty and many or no correct answers. [2]

The remainder of this part addresses a host of topics involved with open-ended problems and approaches. The following sections are addressed:

1. General Thoughts
2. The Authors' Approach
3. Earlier Experiences
4. Developing Students' Power of Critical Thinking
5. Creativity and Brainstorming
6. Inquiring Minds
7. Final Thoughts

General Thoughts

Here are a baker's dozen general thoughts regarding the open-ended problem approach drawn from the files of one of the authors. [3]

1. Abstract reasoning is the ability to analyze information and solve problems on a complex, thought-based level.
2. Software will become increasingly more important.
3. In order to create an individual's intellectual capabilities, one has to nurture and cultivate while educating, which may take decades of effort.
4. To reach the upper levels of science and technology, one needs creativity, imagination, and innovation, which at present is not being nurtured.
5. Wealth will be generated from technological innovations.
6. The labor market is undergoing a historic change, and individuals in the future should exploit this.
7. Everything is possible for the individual who doesn't have to do it.
8. It's okay for a scheme not to work, i.e., it's okay to fail.

9. Chemical engineers in the future will be judged and rewarded by their ability to predict evolving situations and formulate concrete strategies.
10. An important part of success will be to anticipate future situations, evaluate possible outcomes, and set appropriate goals.
11. Many of the old blue-collar factory jobs will disappear.
12. The chemical engineer has to be educated to meet the challenges of this century, and this will require activities that involve creativity, artistic ability, innovation, leadership, and analysis.
13. The chemical engineer who develops good habits of problem solving early in his/her career will save considerable time and avoid many frustrations later in life.

The Authors' Approach

Here is what the authors have stressed to their students in terms of developing problem-solving skills and other creative thinking.

1. Carefully define the problem at hand.
2. Obtain all pertinent data and information.
3. Initially, generate an answer or solution.
4. Examine and evaluate as many alternatives as possible, employing "what if" scenarios [1].
5. Reflect on the above over time.
6. Consider returning to step 1 and repeat/expand the process.

The traditional methodology of solving problems has been described for decades with the following broad stepwise manner:

1. Understand the problem.
2. Devise a plan.
3. Carry out the plan.
4. Look back and (possibly) revise.

Many now believe creative thinking should be part of every student's education. Here are some ways that have proven to nudge the creative process along:

1. Break out of the one-and-only answer rut.

2. Use creative thinking techniques and games.
3. Foster creativity with assignments and projects.
4. Be careful not to punish creativity.

The above-suggested activities will ultimately help develop a critical thinker that:

1. Raises important questions and problems, formulating them clearly and precisely.
2. Gathers and assesses relevant information, using abstract ideas to interpret it effectively.
3. Comes to well-reasoned conclusions and solutions, testing them against relevant criteria and standards.
4. Thinks open mindedly within alternative systems of thought, recognizing and assessing, as need be, their assumptions, implications, and practical consequences.
5. Communicates effectively with others in figuring out solutions to complex problems.

The analysis aspect of a problem remains. It essentially has not changed. The analysis of a new problem in chemical process engineering can still be divided into four steps.

1. Consideration of the process in question.
2. Mathematical description of the process, if applicable.
3. Solution of any mathematical relationships to provide a solution.
4. Verification of the solution.

Earlier Experiences[1,4,5]

The educational literature provides frequent references to individuals, particularly engineers, and other technical fields, that have different learning styles, and in order to successfully draw on these different styles, a variety of approaches can be employed. One such approach for educators involves the use of *open-ended* problems.

The term *open-ended* has come to mean different things to different people in industry and academia. It basically describes an approach to the solution of a problem and/or situation for which there is usually not a unique solution. Three literature sources[6–8] provide sample problems that can be used when this educational tool is employed.

One of the authors of this book has applied this somewhat unique approach and has included numerous open-ended problems in several chemical engineering course offerings at Manhattan College. Student comments for a general engineering graduate course "Accident and Emergency Management" were tabulated. Student responses to the question "What aspects of this course were most beneficial to you?" are listed below:

1. "The open-ended questions gave engineers a creative license. We don't come across many of these opportunities."
2. "Open-ended questions allowed for candid discussions and viewpoints that the class may not have been otherwise exposed to."
3. "The open-ended questions gave us an opportunity to apply what we were learning in class with subjects we have already learned and gave us a better understanding of the course."
4. "Much of the knowledge that was learned in this course is applicable to everyday situations and our professional lives."
5. "Open-ended problems made me sit down and research the problem to come up with ways to solve them."
6. "I thought the open-ended problems were inventive and made me think about problems in a better way."
7. "I felt that the open-ended problems were challenging. I, like most engineers, am more comfortable with quantitative problems than qualitative."

In effect, the approach requires asking questions, to not always accept things at face value, and to select a methodology that provides the most effective and efficient solution. Those who conquer this topic have probably taken first step toward someday residing in an executive suite.

Developing Students' Power of Critical Thinking[1,9]

It has often been noted that chemical engineers are living in the middle of an information revolution. Since the term of the century, that revolution has had an effect on teaching and learning. Educators are hard-pressed to keep up with the advances in their fields. Often their attempts to keep the students informed are limited by the difficulty of making new material available.

The basic need of both educator and student is to have useful information readily accessible. Then comes the problem of how to use this information properly. The objectives of both teaching and studying such information are: to assure comprehension of the material and to integrate it with the basic tenets of the field it represents; and, to use the comprehension of the material as a vehicle for *critical thinking* and *effective argument*.

Information is valueless unless it is put to use; otherwise, it becomes mere data. For information to be used most effectively, it should be taken as an instrument for *understanding*. The process of this utilization works on a number of incremental levels. Information can be absorbed, comprehended; discussed, argued in reasoned fashion, written about, and integrated with similar and contrasting information.

The development of critical and analytical thinking is key to the understanding and use of information. It is what allows the student to discuss, and argue points of opinion and points of fact. It is the basis for the student's formation and development of independent ideas. Once formed, these ideas can be written about and integrated with both similar and contrasting information.

Creativity and Brainstorming

Chemical engineers bring mathematics and other sciences to bear on practical problems and applications, molding materials and harnessing technology for human benefit. *Creativity* is often a key component in this synthesis; it is the spark, motivating efforts to devise solutions to novel problems, design new products, and improve existing practices. In the competitive marketplace, it is a crucial asset in the bid to win the race to build better machines, decrease product delivery times, and anticipate the needs of future generations.[1,9]

One of the keys to the success of a chemical engineer or a scientist is to generate fresh approaches, process and products, i.e., they need to be creative. Gibney[9] has detailed how some schools and institutions are attempting to use certain methods that essentially share the same objective: open students' minds to their own creative potential.

Gibney [9] provides information on "The Art of Problem Definition" developed by the Rensselaer Polytechnic Institute. To stress critical thinking, they teach a seven-step methodology for creative problem development. These steps are provided below: [9]

1. Define the problem.
2. State objective.
3. Establish functions.
4. Develop specifications.
5. Generate multiple alternatives.
6. Evaluate alternatives.
7. Build.

In addition, Gibney [9] identified the phases of the creative process set forth by psychologists. They essentially break the process down into five basic stages:

1. Immersion.
2. Incubation.
3. Insight.
4. Evaluation.
5. Elaboration.

Psychologists have ultimately described the creative process as *recursive*. At any one of these stages, a person can double back, revise ideas, or gain new knowledge that reshapes his or her understanding. For this reason, being creative requires patience, discipline, and hard work.

Delia Femina [10] outlined five "secrets" regarding the creative process:

1. Creativity is ageless.
2. You don't have to be Einstein.
3. Creativity is not an eight hour job.
4. Failure is the mother of all creativity.
5. Dead men don't create.

Panitz [11] has demonstrated how *brainstorming strategies* can help engineering students generate an outpouring of ideas. Brainstorming guidelines include:

1. Carefully defining the problem upfront.
2. Allow individuals to consider the problem before the group tackles it.
3. Create a comfortable environment.
4. Record all suggestions.
5. Appoint a group member to serve as a facilitator.
6. Keep brainstorming groups small.

A checklist for change was also provided, as detailed below:

1. Adapt
2. Modify.
3. Magnify.
4. Minify.
5. Put to other uses.
6. Substitute.
7. Rearrange.
8. Reverse.
9. Combine.

Inquiring Minds

In an exceptional well-written article by Lih [12] entitled "Inquiring Minds", he commented on inquiring minds by saying "You can't transfer knowledge without them." His thoughts (which have been edited) on the inquiring or questioning process follow:

1. Inquiry is an attitude—a very important one when it comes to learning. It has a great deal to do with curiosity, dissatisfaction with the status quo, a desire to dig deeper, and having doubts about what one has been told.
2. Questioning often leads to believing—there is a saying that has been attributed to Confucius: "Tell me, I forget. Show me, I remember. Involve me, I understand." It might also be fair to add: "Answer me, I believe."
3. Effective inquiry requires determination to get to the bottom of things.
4. Effective inquire requires wisdom and judgment. This is especially true for a long-range intellectual pursuit that is at the forefront of knowledge.
5. Inquiry is the key to successful life-long learning. If one masters the art of questioning, independent learning is a breeze.
6. Questioning is good for the questionee as well. It can help clarify issues, uncover holes in an argument, correct factual and/or conceptual errors, and eventually lead to a more thoughtful outcome.

7. Teachers and leaders should model the importance of inquiry. The teacher leader must allow and encourage questions and demonstrate a personal thirst for knowledge.

Ultimately, the degree to which one succeeds (or fails) is often based in part on one's state of mind or attitude. As President Lincoln once said: "Most people are about as happy as they make their minds to be." William Jones once wrote: "The greatest discovery of my generation is that human beings can alter their lives by altering their attitude of mind." So, no matter what one does, it is in the hands of that individual to make it a meaningful, pleasurable, and positive experience. This experience will almost definitely bring success.

Final Thoughts

One of the authors [13], prior of retiring, sought consulting jobs when he was told, "We just can't figure out how to solve the problem." For example, should a heat exchanger be heated with atmospheric or superheated steam? Obviously, it would appear to be better to employ atmospheric steam. But, that may not always be the "best" approach. Tackling and solving these class of problems will only come with experience. And then there is the option of ordering a chemical reactor in assembled form rather than in sections. One would normally select the assembled option, but once again, it might require eliminating walls and/or enlarging small openings. The choice is not clear and analysis is warranted.

The traditional chemical engineering curriculum cannot be totally abandoned. It must still include material to describe the behavior of processes and the ability to design equipment. If the process or problem is complex, he/she must also be able to use approximate methods. Unfortunately, many systems with which the chemical engineer will deal with in the future do not fit simple theory.

The development of the future chemical engineer can be compared to the development of a good basketball player [14]. A basketball player must learn how to dribble and shoot. He must also develop an ability to play hard-nose defense, and he must learn the meaning of teamwork. He must also learn to take orders from his coaches. All these can be worked on and perfected individually, but the complete basketball player does not manifest until all the individual parts are put together to function as a smooth, complete unit. [14] Just as the basketball player needs to work on the individual parts of his skill, the chemical engineer still needs to study the separate operations involved in his field. Chemical engineers must study and understand the basic laws of chemistry and physics. They must know the various types of equipment and the economics involved in the over-all plant process. They must understand the unit operations of fluid flow, heat transfer and mass transfer operations, and other peripheral topics.

What about the chemical engineer sustaining his/her career? MacLean [15] recently provided some career advice that is generally universally recognized. Here is a summary of his baker's dozen (the authors have added three to his 10) pointers:

1. Pick a rigorous college.
2. Pick a future viable career path, not the current popular one.
3. EQ (emotional quotient) is as important as IQ.
4. Be really nice to everyone.
5. Choose your battles very carefully.
6. Be patient and hold your tongue.
7. Do not expect to be rewarded for hard work.
8. Understand your "customer" needs.
9. Do your fair share.
10. Maintain contact.
11. Provide praise (if appropriate) to others.
12. Luck rules; increase your odds.
13. Most importantly, develop an ability to communicate orally and in writing.

Some of the suggestions might be a good fit for some chemical engineers, and some may not apply over their entire career. Think it through.

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