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THE FUTURE OF ENGINEERING EDUCATION
II. TEACHING METHODS THAT WORK

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Deficiencies in engineering education have been exhaustively enumerated in recent years. Engineering schools and professors have been told by countless panels and blue-ribbon commissions and, in the United States, by the Accreditation Board for Engineering and Technology that we must strengthen our coverage of fundamentals; teach more about "real-world" engineering design and operations, including quality management; cover more material in frontier areas of engineering; offer more and better instruction in both oral and written communication skills and teamwork skills; provide training in critical and creative thinking skills and problem-solving methods; produce graduates who are conversant with engineering ethics and the connections between technology and society; *and* reduce the number of hours in the engineering curriculum so that the average student can complete it in four years.[1]

This is an impressive wish list—especially when the last item is included—that cannot possibly be fulfilled using the approach to educating engineers that has predominated in the past 50 years. If, for example, courses continue to be confined to single subjects (heat transfer in one course, thermodynamics in another, environmental engineering in another, technical writing in another, etc.) it will take a six- or seven-year curriculum to produce engineers who have the desired proficiency in the fundamentals and are conversant with methods of modern engineering practice, culturally literate, and skilled in communication. Moreover, if students are assigned only well-defined convergent problems, they will never gain the skills needed to tackle and solve challenging multidisciplinary problems that call for critical judgment and creativity. Finally, even if nothing new is added to the existing curriculum, confining it to four years will be almost impossible unless more efficient and effective ways to cover the material can be found.

The reality is that better teaching methods exist. The literature in general education, technical education, and educational psychology is replete with methods that have been shown to facilitate learning more effectively than the traditional single-discipline lecturing approach. Unfortunately, these developments have so far had relatively little impact on mainstream engineering education. Although their content has changed in some ways and the students use calculators and computers instead of slide rules, many engineering classes in 1999 are taught in exactly the same way that engineering classes in 1959 were taught.

The purpose of this paper is to offer alternatives. The instructional methods to be described have been chosen to meet the following criteria:

- *They are relevant to engineering education.*

  Many innovative instructional methods have been developed for nontechnical courses and emphasize free discussion and expressions of student opinions, with minimal teacher-centered presentation of information. We believe that involvement of students is critical for effective classroom learning;

however, much of the basic content of engineering courses is not a matter of opinion. Educational approaches that emphasize process exclusively to the detriment of content will not be considered.

- *They can be implemented within the context of the ordinary engineering classroom.*

  An instructional approach based entirely on, say, self-paced computer-assisted instruction might be extremely effective—at least for some students—but it might also require a specialized network of workstations that could cost an institution several million dollars to purchase and set up. Such programs will be left off the list. The techniques we describe can be implemented in regular classrooms and laboratories with no tools or devices beyond those routinely available to all engineering instructors.

- *Most engineering professors should feel reasonably comfortable with them after a little practice.*

  It is conceivable, for example, that getting students to role-play molecules in a reactive gas would teach them more about the dynamic behavior of a given system than would a standard lecture. Some instructors find methods like this useful and can manage to pull them off; still, it is safe to say that most engineering professors would never contemplate doing anything like that in their classes. Such methods will not be included in our list of recommendations.

- *They are consistent with modern theories of learning and have been tried and found effective by many educators.*

  The literature is full of articles by professors who have tried new methods and written about the results. However, the validity of a method must remain suspect if the only evidence on its behalf is one person's testimony that "I tried this and liked it and so did the students." The methods to be given are consistent with results of theoretical and/or empirical studies in the cognitive and educational psychology literature, and they have each been implemented successively in engineering classes by independent investigators.

This paper surveys some (but by no means all) instructional methods that meet these criteria. Several excellent references describe other techniques and summarize the supporting research.[2–4]

1. FORMULATE AND PUBLISH CLEAR INSTRUCTIONAL OBJECTIVES[5–10]

Instructional objectives are statements of what students should be able to do to demonstrate their mastery of course material and desired skills. They contain a stem specifying the point at which the mastery should occur, followed by one or more phrases describing the expected behavior, with each phrase beginning with an action verb. For example,

> *When this chapter has been completed , the student should be able to* define *the variables in the ideal gas equation of state in terms a high school senior could understand,* calculate *the value of any one of the variables from given values of the other three,* estimate *the error in the calculated value, and* outline *the derivation of the ideal gas equation from the kinetic theory of gases.*

The common stem of the four objectives in this paragraph is "When this chapter has been completed." An alternative stem might be "In order to do well on the next test." The phrases that define the objectives begin with the verbs *define, calculate, estimate,* and *outline*. Other acceptable verbs include *list, identify, explain (without using jargon), predict, model, derive, compare and contrast, design, create, select, optimize,* and many others.

The behavior specified in an instructional objective must be directly observable by the instructor and should be as specific and unambiguous as possible. For this reason, verbs like *know, learn, understand, and appreciate* are unacceptable. These are critically important goals, but they are not directly observable. For example, if an instructor states that his goal is for his students to understand the first law of thermodynamics, he might be asked how he will know whether or not they do. He would then list the things he would ask them to do to demonstrate their understanding. The items on the list would constitute the instructional objectives associated with the specified goal. If there could be any possible doubt about whether or not an objective has been met, measurement criteria should be included in the defining statement.

Instructional objectives may involve skills that cover a broad spectrum of complexity and difficulty. The *Taxonomy of Educational Objectives (Cognitive Domain)* developed by Bloom and colleagues[10] defines a hierarchy of six levels:

1. *Knowledge*—repeating memorized information
2. *Comprehension*—paraphrasing text, explaining concepts in jargon-free terms
3. *Application*—applying course material to solve straightforward problems
4. *Analysis*—solving complex problems, developing process models and simulations, troubleshooting equipment and system problems
5. *Synthesis*—designing experiments, devices, processes, and products
6. *Evaluation*—choosing from among alternatives and justifying the choice, optimizing processes, making judgments about the environmental impact of engineering decisions, resolving ethical dilemmas

Levels 1–3 are commonly known as *lower-level skills* and Levels 4–6 are *higher-level skills*. Most undergraduate engineering courses focus on Level 3 skills: an analysis of one four-year engineering program showed that 2345 out of 2952 problems assigned (79%) were Level 3 or lower.[11] On the other hand, probable demands on engineering graduates in the coming decades and many of the new ABET accreditation criteria (Engineering Criteria 2000) involve skills at Levels 4–6.[1]

Recommendation

Write instructional objectives for a course (or a section of a course) that encompass both knowledge of content and mastery of the skills you wish the students to develop. At all levels of the engineering curriculum—including the first year—include some higher-level problem-solving skills (e.g. multidisciplinary analysis, design, critical thinking) and the "soft" skills (e.g. oral and written communication, teamwork, social and ethical awareness) specified in EC 2000.[1] Make the objectives as detailed and specific as possible: rather than simply saying that the student will be able to "design a chemical plant," list all the different things the student will be expected to do (look up, estimate, calculate, create, analyze, select, explain) in the course of designing the plant. Make class exercises, homework assignments, and tests consistent with the objectives. Give the objectives to the students to use as study guides.

Justification

Once formulated, instructional objectives reveal which course topics are most important and deserve the greatest coverage, and which ones the students can do little with but memorize and so merit only cursory attention or possibly elimination from the curriculum. Objectives enable instructors to design consistent homework assignments that provide practice in all of the desired skills and tests that assess mastery of the skills. They make ideal study guides for the students: the more explicit you are about what you want the students to be able to do, the more likely they will be to succeed at doing it.[12] The objectives provide an excellent outline of the content of a course to instructors teaching the course for the first time and instructors of subsequent courses. Finally, the instructional objectives for all departmental courses collectively reveal both gaps and redundancies in the curriculum and provide an excellent curriculum overview to accreditation visitors, especially if homework assignments and tests closely follow the objectives.

2. ESTABLISH RELEVANCE OF COURSE MATERIAL AND TEACH INDUCTIVELY

Instructors often start a course by presenting totally new material without putting it in any context. They make no attempt to relate the material to things students already know about from their own experience or from prior courses, nor do they preview how it will be needed to solve problems of the types the students will encounter later in the curriculum or in professional practice. These instructors are pursuing what might be called the "Trust Me" approach to education (as in "Trust me—what I'm teaching you may seem pointless now but in another year or perhaps in four years you'll see why you needed it").

Students tend to study hardest and learn best what they are interested in and believe they have a need to know.[2,3,12–15] Unfortunately, most freshman engineering courses (e.g., chemistry courses that launch the students directly into molecular modeling) and many engineering courses (e.g., introductory fluid dynamics courses that start with momentum balances on differential fluid elements and perhaps even stress tensors) are taught with the Trust Me approach, which stimulates neither interest nor motivation to learn. The fact that many students in these courses appear apathetic and do poorly is a common source of frustration to the instructors, but it should not come as a surprise.

Recommendation

Begin teaching each course and each new topic within it by describing the physical and chemical phenomena to be studied and the types of problems to be solved, if possible using examples familiar to the students. Discuss several realistic situations in which engineers and scientists are required to understand the phenomena and solve the problems. A good way to begin is to divide the class into groups of three or four and have the groups generate as many examples as they can think of in a brief period of time, adding your own to supplement whatever they come up with. For example

> *For the next two weeks we're going to be discussing characteristics of a fluid flowing through a pipe.. In groups of three, come up with as many situations as you can that involve this subject—three people talking, one writing down the ideas. You have one minute—go!*

Give them the allotted time or a little more if they seem to need it, then stop them and collect ideas, listing them without criticism. At least some groups are almost certain to come up with home plumbing, irrigation, oil and coolant flows in engines, municipal water and sewer flows, flow of body fluids, and a variety of industrial examples. Supplement their list with your own. You might then continue as follows:

> *OK, you're now engineers designing a piping system to move fluid from a storage tank to a reactor at a specified rate. What will you need to know or figure out? Same groups, two minutes—go!*

It may occur to some of the groups that they will need to know the density and viscosity of the fluid, the distance from the tank to the reactor, whether the fluid is corrosive or dangerous in some way, the pipe material (aluminum, copper, stainless steel, plastic), and costs of piping, pumps, and power, and they will have to determine the pipe diameter, the required valves, fittings, and flow meters, the kind of pump to use, the size of the pump, and the path of the system. Give hints if necessary, and add items to their list. Spending ten minutes on such an exercise at the beginning of a new topic can go a long way toward motivating the students to pay attention to what will be taking place in the subsequent two or three weeks.

The flow of information in the presentation of course material should generally follow that of the scientific method: begin with induction, proceeding by inference from specifics (facts, observations, data) to generalities (rules, theories, correlations, mathematical models), and then switch to deduction, using the rules and models to generate additional specifics (consequences, applications, predictions).

Justification

Our goal in teaching is to get information and skills encoded in our students' long-term memories. Cognitive research tells us that people learn new material contextually, fitting it into existing cognitive structures,[13–15] and new information that cannot be linked to existing knowledge is not likely to be retained. Moreover, once information is stored in long-term memory, cues are required for us to recall and use it. Linking the new material to familiar material provides a natural set of cues.

The motivational and learning benefits of providing context, establishing relevance, and teaching inductively are supported throughout the literature on cognitive and educational psychology and effective pedagogy.[15,16] Ramsden and Entwistle[12] note the motivational effectiveness of "vocational relevance," and the same authors show that establishing relevance is one of the factors that induce students to adopt a "deep" (as opposed to superficial) approach to learning.[12,17]

Inductive teaching (wherein the information flow generally proceeds from specifics to generalities) takes several forms in the literature, variously known as discovery learning, inquiry learning, problem-based learning, just-in-time learning, and the case study method. Problem-based learning (PBL), which involves students working in teams on projects built around realistic problems, has been extensively described and shown to be effective in science, engineering, and medicine.[18–23] This approach is discussed in greater detail in the next paper in this series.

The literature on learning styles also supports the recommendations in this section.[24–33] Kolb[27–29] suggests "teaching around the cycle." starting with a concrete experience, documenting our observations, creating an abstract model, and then experimenting and testing the model. This cycle has been used to design a college-wide instructional program in engineering.[30,31] Establishing the relevance of new material before going into the details can provide the concrete experience that starts the learning cycle.

3. BALANCE CONCRETE AND ABSTRACT INFORMATION IN EVERY COURSE

Material in engineering courses may be categorized as being *concrete*—facts, observations, experimental data, applications—or *abstract*—concepts, theories, mathematical formulas and models. Most engineering courses contain material in each category, but the balance varies considerably from one course to another and from one instructor to another in a given course.

In recent decades the balance between the two categories in the engineering curriculum has been shifting toward abstraction. The old courses on industrial processes and machinery have been largely replaced with courses that emphasize mathematical expressions of fundamental scientific principles. While this movement may have initially had the effect of correcting an imbalance, it has proceeded to an extent that has negative consequences for many students. The problem with introducing abstraction that is not firmly grounded in the student's knowledge and experience has been described in the preceding section: the new material is not linked to existing cognitive structures and so is unlikely to be transferred to long-term memory.

Recommendations

Balance concrete and abstract content in the presentation of all engineering courses. Most courses currently contain a reasonable level of abstraction, so the challenge is generally to provide sufficient concrete material for those who need it. Some ideas for doing so follow.

- Do everything listed under the category of establishing relevance in Suggestion #2.
- Continue to intersperse concrete illustrations and applications throughout a theoretical development rather than waiting until the final formula has been derived. When possible, tie the examples back to the "real-world" systems and situations introduced in the motivating introduction to the subject.

- When illustrating how formulas and algorithms are applied, use numbers rather than algebraic variables in at least the first example. The greater the level of generality of the theory, the greater the need for specificity in the examples. Some students—specifically, sensing learners—understand "5" at a level that they may never understand "*x*".[25,32,33]

- *Provide visual illustrations and demonstrations of course-related material as possible.* Most students get a great deal more out of visual information than verbal information (written and spoken words and mathematical formulas).[25] Show pictures, sketches, schematics, plots and flow charts, and computer simulations of process equipment and systems. Take the class to the local boiler house and point out pumps, flowmeters, boilers, heat exchangers, refrigeration units, and turbines. Bring demonstrations into class, such as those described by Wood[34] for heat transfer and Kresta[35] for fluid mechanics.

- *Never venture too far from the realm of experimentation.* In abstract subjects like thermodynamics and process control, for example, it is easy for the students to drown in the alphabet soup of variables that bear no apparent relationship to anything one can measure in a laboratory or plant (e.g. entropy, free energy, and transfer functions). It is important to remember that the goal of all theories is ultimately to correlate data from measurements on physical systems and to predict the outcomes of future measurements. As each abstract variable is introduced, provide examples of how it could be determined experimentally and how values of measured variables can be predicted from known values of the abstract variables, and give such problems as homework assignments. Once the students have manipulated a given variable or function in a variety of contexts, its meaning can be assumed to be anchored in memory, but in the absence of such examples and exercises no such assumption can be made.

Just as overemphasizing mathematical formulations of course principles works against the sensing learner, overemphasizing facts and computational algorithms and short-changing conceptual understanding works against intuitive learners.[33] (This concrete/abstract imbalance is also not in the sensors' best interests, but it is less likely to make them uncomfortable.) Engineering students are not generally overloaded with spare time. If they can get away with memorizing problem solutions without understanding or questioning the underlying concepts and methods, many will do it.[17]

One way to help students gain a deeper understanding of course material is to ask questions that require such an understanding, first in class problems and homework and then on tests. For example:

- *Eq. (8-34) in the textbook is presented with only a sketchy explanation of where it comes from. Derive it, starting with Eq. (8-5)*

- *In Monday's handout there are a number of suggestions to "Prove" or "Verify" some statement or result. At least one of them will show up on the next test. I won't go over them unless asked.* (or, *I'll go over them during my office hours and only if you demonstrated that you've attempted them yourself*).

- *Explain what a vapor pressure is in terms a high school senior could understand.*

- *Why do you feel comfortable in 20°C air and freezing in 20°C water? Your explanation should involve several concepts introduced in this course.*

- *Make up and solve a problem related to the material just covered.*[36,37] *The problem must be original, but you can get ideas and help from one another and from me.* Start simply the first time you do this in class, and gradually build in more depth. For example,

  – *Make up but don't solve a problem involving Raoult's law.*

  – *Make up and solve a problem involving Raoult's law.*

  – *Make up and solve a problem involving Raoult's law. If your problem is straightforward (given this, calculate that) and there are no mistakes you'll get a C; to earn full credit the* *problem should involve a realistic situation and should require the problem solver to really understand the material.*

– *Make up and solve a problem that involves both Raoult's law and what you covered during the last two weeks of your organic chemistry course.*

You may not get many good problems the first time or two you do exercises like these, but if you provide feedback and give the class examples of successful efforts, many students will surprise you (and themselves), both by the quality of their problems and by how thoroughly they learned the material in the course of the exercise.[36,37]

As noted in the previous section, a good way to achieve concrete/abstract balance is to "teach around the cycle."[26–31] When presenting a new concept, start with a physical demonstration or real-world example, model the results, test the model through active experimentation and explore its implications. You might also find it worthwhile to have students measure their own learning styles and talk about the implications. The more they understand their preferences, the more they can capitalize on the strengths of their preferred styles and work to build their capabilities in their less preferred styles. Felder and Soloman's *Index of Learning Styles*[38] and Keirsey's *Temperament Sorter*[39] are accessible on-line and easy to use for this purpose.

Justification

Piaget[40] suggests that human capabilities evolve in stages, beginning with the *sensory-motor* stage (about age 2) and proceeding through *pre-operational* (ages 4 through 7) and *concrete operational* (about age 12) stages to the *formal operational* stage. Concrete operational thinkers can think logically in terms of objects but have difficulty replacing objects by symbols. They can acknowledge different viewpoints and cause-effect logic but they have trouble generalizing through verbal or proportional reasoning. *Formal operational* thinkers can replace objects with symbols, generalize and work with abstract concepts, use verbal and proportional reasoning, and derive cause-effect relationships from results of experiments.

Piaget stated that the shift from concrete operational to formal operational thinking should occur by age 12; however, more recent observations suggest that many first-year college students have not yet made it. Williams and Cavallo,[42] working with freshmen in physics courses, found that most of their subjects were concrete operational, incapable of grasping abstract concepts that were not firmly embedded in concrete experience. By including concrete examples in our teaching and explicitly showing how they can be generalized, we can help students make the shift from concrete to formal operational thinking.[43]

Learning style differences also provide justification for establishing a good concrete/abstract balance in every engineering course.[24–26,32,33] Sensing learners tend to be practical and methodical; intuitors tend to be imaginative and quick-thinking. Sensors are more comfortable with concrete information (facts, data, "real-world" phenomena) than with abstractions (theories, concepts and models), and the converse is true of intuitors. Both sensing and intuitive learners make excellent engineers, although they tend to gravitate to different specialties. Sensors make excellent experimentalists and production engineers; intuitors do well in design and theoretical research and development, and both types may become excellent managers and administrators. Industry and academia need individuals with both type preferences.

Most engineering undergraduates are sensors while most engineering professors are intuitors.[44,45] Most intuitive professors and even many of the sensing professors teach in an intuitor-oriented manner, emphasizing theories, mathematical models and abstract prose to students who respond best to concrete examples, well-established problem-solving procedures, and material that has a clear connection to the "real-world" (a classic sensor's phrase). This mismatch has several unfortunate consequences for the sensing learners. Faced with an incessant barrage of material that seems remote and abstract, they have difficulty absorbing the material, become bored in class, tend to do poorly on tests (frequently running out of time on them) and tend to get lower grades in engineering courses than their intuitive counterparts, even though both types do equally well as practicing engineers.

Making courses overwhelmingly abstract is also a disservice to the intuitors. Even if they intend to go on to graduate school and research careers, they need to strengthen their sensing skills (observation of and attention to details, careful methodology, replication of measurements and calculations), and they will not do so if they are not challenged to do so in their courses.

4. PROMOTE ACTIVE LEARNING IN THE CLASSROOM

In the traditional approach to higher education, the professor dispenses wisdom in the classroom and the students passively absorb it. Research indicates that this mode of instruction can be effective for presenting large bodies of factual information that can be memorized and recalled in the short term. If the objective is to facilitate long-term retention of information, however, or to help the students develop or improve their problem-solving or thinking skills or to stimulate their interest in a subject and motivate them to take a deeper approach to studying it, instruction that involves students actively has consistently been found more effective than straight lecturing.[2,3,46,47] The challenge is to involve most or all of the students in productive activities without sacrificing important course content or losing control of the class.

Recommendation

Several times during each lecture period, ask the students to form into groups of 2–4 where they are sitting and give them brief exercises that last anywhere from 30 seconds to 3 minutes. The exercises may involve answering questions of the type instructors routinely ask the class as a whole or they may call for problem solving or brainstorming. For example,

- *Outline a strategy for solving the problem just posed.*
- *Draw a flowchart (schematic) for the process just described.*
- *Think of as many practical applications as you can of this (system, device, solution method).*
- *Get started on the solution of the problem and see how far you can get with it in two minutes.*
- *What is the next step in the derivation?*
- *Complete this calculation.*
- *Prove or verify this result.*
- *Suppose you carry out experimental measurements and the results fail to agree with the theoretical formula we just derived. Think of as many possible explanations as you can.*
- *What questions do you have about this material?*

The groups should generally be given a very short time to respond—long enough to think about the question and to begin to formulate an answer but not necessarily to work out complete solutions

Vary the format of these exercises to prevent their becoming as tedious and ineffective as straight lecturing. Assign some to pairs, some to groups of three or four, and some to individuals. Sometimes ask students to work on a problem individually and then compare their answers with a partner ("think-pair-share"). Sometimes give a rapid succession of such exercises, and sometimes lecture for 10-15 minutes between exercises.

To maximize the likelihood that most or all of the students will be actively involved and that they will remain on task, *call on several individuals or groups to give their responses when the allotted time period has elapsed.* If you only call for volunteers to share responses, the students will know that the answer will eventually be forthcoming and will have no incentive to participate in the activity, and many will not; however, if they know that any of them could be called on, fear of embarrassment will induce most of them to do the work so that they will be ready with something if they are chosen.

Active learning methods make classes much more enjoyable for both students and instructors. Even highly gifted lecturers have trouble sustaining attention and interest throughout a 50-minute class. After 10-20 minutes in most classes, the students' attention starts to drift, and by the end of the class boredom is rampant. Even if the instructor asks questions in an effort to spark some interest, nothing much happens except silence and avoidance of eye contact. Tests of information retention support this picture of what happens in terms of recall. Immediately after a full lecture, students were able to recall about 70% of the content presented in the first ten minutes, but only 20% of the content of the last ten minutes.[2]

When active learning exercises are interspersed throughout a lecture, the picture changes. Once a class accustomed to group work gets started on a problem, the classroom atmosphere is transformed: discussions, arguments, and occasional laughter can be heard, all sounds of learning taking place. Even students who may not be doing much talking are engaged in thinking about the question at hand instead of just mechanically transcribing notes. Just five minutes of such activities in a 50-minute class can be enough to keep the students attentive for the remaining 45 minutes of lecturing. Many references offer specific suggestions for incorporating active learning exercises in the classroom.[46–50] Felder[51,52] and Woods[53] discuss the implementation of active learning in large classes, and Felder[51] discusses how to incorporate active learning without sacrificing content coverage.

Several authors have developed more formal active learning approaches. One is TAPPS (thinking-aloud pair problem solving), an activity in which pairs of students work their way through a problem solution[54]; another is *the Osterman feedback lecture*, wherein two 20-minute mini-lectures are separated by a 10 minute activity, the latter usually being a short problem that requires the students to have learned certain material before class[18]; and still another is *Team Learning*, a more formal cooperative learning structure in which student teams work on structured learning projects in every class session.[55] All of these techniques require more time and training to implement than the brief turn-to-your-neighbor exercises described previously, but the potential return in depth of learning is greater.

Justification

The literature supporting the notion that active, student-centered learning is superior to passive, teacher-centered instruction is encyclopedic.[13,14,46–48] People acquire knowledge and skills through practice and reflection, not by watching and listening to others telling them how to do something. Straight lecturing may succeed at promoting short-term factual recall, but active approaches have consistently been shown to be superior for promoting long-term retention of information, comprehension, problem-solving skills, motivation to learn and subsequent interest in the subject. Active learning is one of the seven, evidenced-based recommendations for improving learning summarized by Chickering and Gamson[56], and the active learning exercises described above also provide prompt feedback, another of the recommendations.

5. USE COOPERATIVE LEARNING

Cooperative learning (CL) is an instructional approach in which students work in teams on a learning task structured to have the following features[48]:

1. *Positive independence*. There must be a clearly defined group goal (complete the problem set, write the lab report, design the process) that requires involvement of every team member to achieve. If anyone fails to do his/her part, everyone is penalized in some manner.
2. *Individual accountability*. Each student in the team is held responsible for doing his/her share of the work *and* for understanding everyone else's contribution.

3. *Face-to-face promotive interaction*. Although some of the group work may be parceled out and done individually, some must be done interactively, with team members providing one another with questions, feedback, and instruction.
4. *Appropriate use of interpersonal and teamwork skills*. Students should be helped to develop leadership, communication, conflict resolution, and time management skills.
5. *Regular self-assessment of team functioning*. Teams should periodically be required to examine what they are doing well together and what areas need improvement.

Cooperative learning exercises may be performed in or out of class. Common tasks for CL groups in engineering are completing laboratory reports, design projects, and homework assignments in lecture courses. Only one problem set or report is handed in by a group and one group grade is assigned to the project, but adjustments for individual team citizenship (or lack thereof) can and should be made. Pre-examination group study sessions can also be set up to meet out of class, with bonus points being awarded to members of groups for which the team average test grade exceeds a specified value.

Recommendations

The following suggestions are based on material in Johnson, Johnson, and Smith,[48] Felder and Brent,[57,58] and Millis and Cottell.[59]

- *Explain to students what you are doing and why*. As with in-class active learning methods, cooperative homework may not be welcomed enthusiastically by all students. Some regard it as a game the instructor is playing at their expense or an experiment with them as the guinea pigs, and some may complain that the instructor is not doing his/her job (which they see as lecturing to them on everything they will need to know for the tests). Felder and Brent[60] discuss the origin and forms of student resistance to active and cooperative learning and suggest strategies for defusing and eventually overcoming the resistance. Twenty minutes on the first day spent giving some of the reasons for using the approach (e.g., it prepares students to function in the environment in which engineers work) and the proven educational benefits to students (e.g., higher grades and lower dropout rates) can go a long way toward overcoming the resistance. Another option is to run a mini-workshop on managing change.[18,19]
- *Assign some or all homework to teams of 3-4 students*. In teams of two, one person tends to dominate and there is usually no good mechanism for resolving disputes, and in teams of five or more someone is usually left out of the process. Collect one assignment per group.
- *Form the groups yourself.* Considerable research shows that instructor-formed teams on average function better than self-selected teams. When students self-select groups, the top students often find one another and form groups, leaving the weak students to shift for themselves, which is unfair. Also, good friends find each other, leading to situations in which one or two students are never fully integrated into the team. The ideal team is heterogeneous in ability (which we will shortly say more about), with team members who have common interests and common blocks of time that they can meet outside class. Particularly in the freshman and sophomore years, when most attrition from the curriculum occurs, underrepresented minorities (including women in engineering) should not be isolated in teams. SAT or ACT scores or grades in prerequisite courses may be used as measures of ability, or a diagnostic test given early in the course may be used for the purpose of forming teams.
- *Form teams that are heterogeneous in ability level.* The members of a team of only weak students are obviously at a disadvantage (although sometimes they might do surprisingly well), and the members of a uniformly strong team may choose to divide up the homework and to communicate only cursorily with one another. Neither group receives the full benefits of cooperative learning. In a mixed-ability group, the weaker students gain from seeing how better students study and approach

problems, and the stronger students usually gain deeper understanding of the subject through their attempts to explain the material, a phenomenon familiar to every professor.

- *Assign team roles that rotate with each assignment*. Three indispensable roles are the *manager* (organizes the assignment into subtasks, allocates responsibilities, and keeps the group on task, the *recorder* (writes the final report or problem solution set, or for large projects, assembles the report), and the *checker* (proofreads and corrects the final report before it is submitted). Other roles that may be performed separately or combined with one of the preceding ones include *group process monitor* (makes sure that every team member is contributing and that all contributions are acknowledged by the others, verifies that every team member understands each part of the completed assignment), and *skeptic* (plays the role of devil's advocate, suggests alternative possibilities, keeps the group from leaping to premature conclusions). Only the names of the students who actually participated should appear on the solution, with their team roles for that assignment identified. In a lecture course, the roles should rotate with each assignment so that a student cannot repeat as (say) manager until every other team member has held that position.

- *Promote positive interdependence*. Assign roles. Provide only one set of materials and require only one team product. Provide specialized training to individual team members on different aspects of the project that they must then bring back to the group effort (this technique is known as "jigsaw" in the cooperative learning literature). Give bonuses on tests to groups in which the team average exceeds 80 (or some other specified value). Randomly select one member of each group to present a problem solution or report on a specific aspect of the project and give everyone in the group the grade earned by that individual. If you use the last strategy (which also promotes individual accountability), tell the students well in advance that you plan on doing so but do not provide much advance notice of which students will present on which parts of the assignment.

- *Promote individual accountability.* Give primarily individual tests (although not necessarily all of them—especially if the groups are heterogeneous in ability; some pair or group testing promotes positive interdependence). Call randomly on individual group members to present their group's results. Use peer assessment to adjust team grades for individual effort and/or citizenship.[59,61]

- *Get teams to assess how well they are functioning.* Periodically ask the students to spend five to ten minutes at the end of their work session assessing their performance, identifying their strengths and setting goals for improvement.[19,62,63] A summary of the outcome might be included with the group problem solution or in journals on the group process.

- *Consider doing some testing of pairs or groups*. One mechanism is to administer and score an individual test and then to allow CL teams to retake the test (perhaps as a take-home exam) to earn additional points. The advantage of this procedure is that most students will achieve a deeper understanding of how to solve all the test problems; the disadvantage is that it requires more grading. Dekker and Stice[64] recommend giving tests to pairs of students as an alternative to individual tests and offer ideas for structuring such tests.

- *Do not re-form groups too often.* A team should remain together for at least a month in order to evolve through the "form, storm, norm, and perform" evolution of team development. If students know that they will only have to remain in a team for two or three weeks, they will have little incentive to confront and overcome the interpersonal problems that commonly arise in team development. If, however, they know they are going to be together for a longer period of time, they are forced to deal with the problems by establishing norms, developing strategies for coping creatively with conflict, and taking advantage of and valuing individual talents and learning styles.

- *Provide an escape mechanism for teams having severe difficulties.* Roughly halfway through the semester, announce that you will dissolve all of the teams and form new ones, except that a team may stay together if each member sends a note to the instructor expressing a desire to do so. Typically all but the most highly dysfunctional teams elect to remain together, and the problem students in the groups that dissolve often change their behavior in their new groups. Consider instituting mechanisms for firing uncooperative students and for quitting uncooperative teams when all other avenues (including instructor intervention) have been exhausted and prior warnings have been given.[58]

- *Do not assign course grades on a curve*. If students recognize that by helping someone else they could be hurting themselves (as is the case when grades are curved), they may be inclined to avoid cooperation, making it less likely that the benefits of cooperative learning will be realized. On the other hand, if they are guaranteed a given grade if they meet a specified standard (for example, a weighted average grade of 88 or better for an A), they have every incentive to help their teammates.
- *Start small and build*. If you have never used cooperative learning and you are not working with a colleague who is experienced in this approach, you might consider beginning on a relatively small scale, with several assignments done by groups and the rest done individually. Once you begin to gain confidence, increase the level of your involvement to a point that feels comfortable to you. When problems arise, remember to consult references on cooperative learning for ideas about how to deal with them.

Justification

Most engineering is done cooperatively, not individually, and technical skill is often less important than interpersonal skill in getting the job done. In survey after survey, representatives of industry place communication and teamwork at the top of their lists of desirable skills for new engineering graduates. If teamwork is such a critical part of what engineers do, surely engineering school should provide some guidance in how to do it.

Cooperative learning may be the most thoroughly researched instructional method in all of education, and a vast and still rapidly growing body of research supports the effectiveness of the approach.[48,57,59,65–68] Studies have shown that relative to students taught traditionally (that is, primarily with lectures and individual homework), cooperatively taught students tend to have better and longer information retention, higher grades, more highly developed critical thinking and problem-solving skills, more positive attitudes toward the subject and greater motivation to learn it, better interpersonal and communication skills, higher self esteem, lower levels of anxiety about academics and, if groups are truly heterogeneous, improved race and gender relations. Another benefit is that when homework is done cooperatively, there are three to four times fewer assignments to grade.

Felder et al.[58,68] report on a longitudinal study comparing the conventional instructor-centered approach with an alternative approach that combined all of the methods recommended in this paper. Students experiencing the alternative approach outperformed students experiencing the conventional approach in their academic performance, development of higher-level thinking skills, retention in chemical engineering, and attitudes toward their educational experience.

A variety of factors account for the observed benefits of cooperative learning. Weaker students working individually are likely to give up when they get stuck; working cooperatively with stronger students to assist them, they keep going to completion. Many strong students tend to do the minimal work required to complete the assignment, which may not require deep understanding of concepts; when faced with the task of explaining and clarifying material to weaker students, they often find gaps in their own understanding and fill them in. Students working alone may tend to delay completing assignments or skip them altogether; when they know others are counting on them, they are often driven to do the work on time.

6. GIVE CHALLENGING BUT FAIR TESTS

Although we might wish it were otherwise, for many of our students tests are the primary motivation to study. The students may attend every class and complete all the assignments, but it is their preparation for the tests that determines the breadth and depth of their learning. The burden is on the instructor to make the tests sufficiently comprehensive and challenging to push each student to learn to the greatest extent of which he or she is capable.

But just as tests can motivate students to learn at a deep level, they can also lead to student demoralization and hostility (both of which correlate with poor performance) if they are perceived by the students as being unfair. The two most common types of tests in this category are tests that are too long and tests that contain surprises—problems with twists unlike anything the students have seen before and problems that call for skills that were never taught in class or required on homework assignments.

Some students—sensing learners on the Myers-Briggs Type Indicator and the Felder-Silverman Learning Styles Model[24–26,32,33]—work more systematically and slowly than the intuitive learners who are their counterparts. On tests, the sensors read and reread problem statements, often take a relatively long time to formulate their problem-solving strategies, and check their calculations carefully. This methodical approach will make many of them excellent engineers and experimental scientists, but it frequently leads to their running out of time on long tests. Nothing infuriates students more than studying hard and being well prepared for a test and then getting a low grade because they lacked sufficient time to demonstrate their understanding. A student who gets a D on a one-hour test that she could have gotten an A on if two hours had been allowed deserves the A: students who do not understand the material at an A level will not earn an A on the test regardless of how much time they are given.

Students also resent surprises on tests. The functions of tests are to motivate and help students to learn what the instructor wants them to learn and to enable the instructor to assess the extent to which they have succeeded in doing so. When students understand the material for which they have been prepared but do poorly because they cannot figure out a "tricky" problem on the spot, they see themselves—rightfully—as having been cheated by the instructor.

Thinking and problem-solving skills—and speed in problem solving, for that matter—are only developed through practice and feedback: testing students on skills they have not had an opportunity to practice is unfair. There is neither empirical evidence nor logic to support the argument that long and tricky tests assess students' potential to be successful engineers or help students become better problem solvers. This does not mean that we should construct easy tests, which do not motivate students to learn at a deep level. It is rather to set the bar high but to teach in a manner such that all students who have the ability to meet the challenge can do so.

Recommendations[2,3,69]

- *Give the students instructional objectives for each test in the form of a study guide:* ("In order to do well on this test, you should be able to…"). Make the list comprehensive and challenging. Include objectives that involve all of the basic types of calculations they should be able to perform, concepts they should be able to explain without using jargon, formulas they should be able to derive, derivations they should be able to explain step-by-step, familiar phenomena that they should be able to interpret in terms of course concepts, and anything else you might call on them to do on the test.[5]
- *When writing the test, consult the instructional objectives and make sure that 10–15% of the test covers the more challenging material in the study guide* (which will allow discrimination between the A-level and B-level students). If the students have the study guide at least a week before the test—and preferably longer than that—and the objectives provide the basis of the test construction, there will be no surprises. The test will be just as challenging or more so than it would otherwise have been, except that now the challenge is to the students' conceptual understanding rather than to their speed or puzzle-solving ability.
- *Always work a test out yourself from scratch when you have finished writing it, timing how long it takes to do it.* This burdensome exercise is the *only* way to discover the overspecified and underspecified problems, the erroneous or ambiguous problem statements, the numerical calculations

that take large amounts of time but show very little about conceptual understanding, and the appropriateness or inappropriateness of the level of difficulty of the entire test. The alternative is for these problems to show up when the test is being given, which leads to disasters of the type all instructors and students have experienced and do not wish to experience again.

- *Minimize speed as a factor in performance on tests*. For quantitative problem-solving tests, you should be able to work out test in less than one-third of the time the students will have to do it, and if the test is particularly difficult or involves many numerical calculations, a one-fourth rule might be more appropriate. If it takes you longer than that, then either find a longer time slot in which to administer the test or consider eliminating questions, presenting some formulas instead of requiring derivations, and asking for solution outlines rather than complete calculations.
- *Do not test skills that students have not had a chance to practice.* Don't give all homework problems at Bloom Level 3 and then put Level 4 questions on the test. Don't require numerical solutions on all homework problems and then ask students for qualitative solution outlines on the test. Don't give students problems with extraneous data on the test unless the students have worked on similar problems in the homework. If picking important material from long readings is a skill you want your students to develop, give them training and practice in it—don't just tell them that they're responsible for everything in their 500-page text and make them guess what you plan to ask them to do. If you think ability to solve quantitative problems quickly is an important skill (it is generally not that important in engineering practice), then give the students training and practice in speed-solving in class and on the homework before you make it a primary criterion for doing well on the tests.
- *Even if you curve grades, if the average is in the 50–60 range or below consider the possibility that it was a poor test or that you did a poor job of preparing the students for it*. If you decide that either is the case, consider adding a fixed number of points to each student's grade to bring the top grade or the average grade to a value of your choosing. Alternatively, if most students missed the same problem, announce a quiz for the following week that will be a variation of that problem and add the results to their test grades.

Justification

Education should not be viewed as a mystery religion. There is no pedagogical value in making students guess what they are supposed to know and understand or in testing them on skills in which they have received no training. When students know explicitly what is expected of them—whether it be straightforward or higher-level or ill-defined problem solving, critical or creative or multidisciplinary thinking, or anything else—and they are given practice and feedback in the specified skills, the odds that they will be able to meet the expectations go up. Even though the tests may be harder, the average student performance will be better than it would have been if the tests were exercises in speed and guessing ability, student morale and motivation will increase, and the students who get low grades will be much more inclined to take responsibility for their poor performance than to blame the test or the instructor.

7. CONVEY A SENSE OF CONCERN ABOUT THE STUDENTS' LEARNING

The social environment in a class—the nature and quality of interactions between the students and the instructor and among the students—can have a profound effect on the quality of learning that takes place in the class.[56,70–75] In his monumental study *What Matters in College*,[70] Alexander Astin found that the quality of interactions between students and instructors in and out of class was the factor that correlated most highly with almost every positive learning and attitude outcome he considered. If students believe that an instructor is concerned about them and has a strong desire for them to learn the course material, the effects on their motivation to learn and their attitudes toward the course, the subject and the instructor can be profound. The suggestions that follow are all known to instill such a belief. We suggest that you consider all of them and try to adopt the ones with which you feel comfortable.

Recommendations

- *Learn the students' names.* Taking the trouble to learn names and use them in and out of class conveys a sense of respect for the students as individuals. Their motivation to do well in your course is likely to increase considerably once they realize that you know who they are. Use place cards or seating charts, take and label photographs of the class, or ask students to bring in photocopies of their student identification cards or drivers licenses and use them to help you learn the names quickly.
- *Make yourself available.* Announce office hours and keep them; if you have to miss them, announce it in advance and schedule replacement hours if possible. Encourage students to contact you during your office hours or by e-mail, perhaps insisting that they do so at least once during the first two weeks of the course. Come to class a few minutes early to answer any questions the students may have or just to chat.
- *If you use nontraditional methods like cooperative learning, explain how what you are doing has been shown to lead to improved learning and/or improved preparation for their careers.* References given in this paper—e.g., Felder and Brent[60]—provide supportive material for such explanations.
- *Celebrate the students' achievements.* When a class does well on a test or you get a number of creative solutions to homework problems, offer commendations. When your students win awards or write articles in the school paper, congratulate them publicly.
- *Collect periodic feedback and respond appropriately to it.* Collect midterm evaluations, using either simple open-ended questions (*What has been helping you learn in the course? What has been detracting from your learning? What changes would improve the course for you?*) or a more formal instrument like the *Course Perceptions Questionnaire*.[75] Periodically collect "minute papers": at the end of a class, have individual students or pairs take a minute or two to write (anonymously) (*i*) the one or two main ideas presented in the lecture, and (*ii*) the muddiest point or concept. Use the responses to monitor how the class went and to plan the next class. In large classes, use ombudspersons—class representatives who report to you periodically about how well the teaching and learning is going. Regardless of the feedback mechanism chosen, summarize the most common suggestions, share them with the class, accept those you can and explain why you cannot accept the others.
- *Let students participate in learning and performance assessment.* Give choices on assignments (e.g., problem sets or projects) and tests (e.g., solve any three of the following four problems). Have students critique one another's drafts of assignments or lab reports before the final versions are turned in to you. Let them create potential examination questions, and use one of them on the actual exam. Have them assess their own performance and the performance of their colleagues in team-based projects.[61] Let them contract for the relative weighting of the term work and the final examination.[19,76,77]
- *Maintain a sense of respect for the students, individually and collectively.* Avoid belittling or sarcastic remarks about their responses to questions, performance on tests, behavior in class, or anything else. If you are disappointed with any or all of them, express your disappointment calmly and respectfully. Avoid comments that involve the slightest trace of disparagement or stereotyping directed at students of a particular race, gender, or sexual orientation, or with students who are disabled in any way. If you fail to follow this recommendation, doing everything else recommended in the paper may not be enough to salvage the class.

Justification

The term "caring" or its synonym "concern" show up in virtually every published study of what students consider to be effective teaching. In a review of nearly 60 studies of students' descriptions of effective teachers, Feldman[78] found eight core characteristics in most lists: concern for students, knowledge of subject, stimulation of interest, availability, encouragement of discussion, ability to explain clearly, enthusiasm, and preparation. Factor analysis of rating scales show four generic factors across disciplines: skill (ability to communicate), rapport (empathy, concern for students), structure (class organization, course presentation), and load (workload).[79] No matter what your teaching style may be—flashy or congenial or scholarly—if students believe you care about them, most will be motivated to learn what you are teaching. If you convey a sense of not caring, then no matter how brilliantly or entertainly you lecture, far fewer will be so motivated.

SUMMARY

We have discussed a wide variety of teaching techniques that have been repeatedly shown to be effective in the context of engineering education. The techniques are variations on the following main themes:

1. Formulate and publish clear instructional objectives.
2. Establish relevance of course material and teach inductively.
3. Balance concrete and abstract information in every course.
4. Promote active learning in the classroom.
5. Use cooperative learning.
6. Give challenging but fair tests.
7. Convey a sense of concern about students' learning.

We do not claim that our suggestions constitute a comprehensive list of proven effective teaching methods. Such a list would be encyclopedic and would be comprehensive only until the appearance of the next issue of any journal on education. We also do not claim that adopting all of the suggestions will guarantee that all students in a class will perform at a high level or even that they will all pass. The performance of an individual student in a class depends on a staggering variety of factors, many of which are out of the instructor's control; moreover, an instructor who sets out to implement *all* of the suggestions in this paper is likely to be overwhelmed in the attempt and to end by implementing none of them.

Our hope is that readers will consider all of the suggestions in the paper in light of their teaching styles and personalities and attempt to adopt a few of them in the next course they teach, and then perhaps a few more in the course after that. While we cannot predict the extent to which the techniques will succeed in achieving the instructors' objectives, we can say with great confidence that their use will improve the quality of learning that occurs in those classes.

IF YOU GET ONE IDEA FROM THIS PAPER

Writing formal instructional objectives and using active and cooperative instructional methods offers a good prospect of equipping your students with the knowledge and skills you wish them to develop.

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