THE INTELLECTUAL DEVELOPMENT OF SCIENCE AND ENGINEERING STUDENTS 2. TEACHING TO PROMOTE GROWTH*

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ABSTRACT

As college students experience the challenges of their classes and extracurricular activities, they undergo a developmental progression in which they gradually relinquish their belief in the certainty of knowledge and the omniscience of authorities and take increasing responsibility for their own learning. At the highest developmental level normally seen in college students (which few attain before graduation), they display attitudes and thinking patterns resembling those of expert scientists and engineers, including habitually and skillfully gathering and analyzing evidence to support their judgments. This paper proposes an instructional model designed to provide a suitable balance of challenge and support to advance students to that level or close to it. The model components are (1) variety and choice of learning tasks; (2) explicit communication and explanation of expectations; (3) modeling, practice, and constructive feedback on high-level tasks; (4) a student-centered instructional environment; and (5) respect for students at all levels of development.

Keywords: Intellectual development, Baxter Magolda's model, Perry's model

I. INTRODUCTION AND REVIEW

According to a model of intellectual development formulated by Marcia Baxter Magolda [1], college students may be found at any of four developmental stages, exhibiting either of two gender-related patterns of behavior in all but the last stage.

- **Absolute knowing**. All knowledge that matters is certain; all points of view are either right or wrong. Authorities have The Truth and the responsibility to communicate it, and the students' job is to memorize and repeat it. In the *mastery pattern* (exhibited by more men than women), students tend to raise questions to make sure their information is correct and challenge deviations from their view of the truth, and in the *receiving pattern* (more women than men), students are more likely to simply take in and record information without questioning or challenging it.
- **Transitional knowing.** Some knowledge is certain and some is not. Authorities have the responsibility to communicate the certainties, and the students must make their own judgments regarding the uncertainties. In the *impersonal pattern* (more men than women), students make judgments using a logical procedure prescribed by authorities and believe that they deserve full credit if they follow that procedure, regardless of the clarity of their reasoning and the quality of their supporting evidence. In the *interpersonal pattern* (more women than men), students base judgments on intuition and personal feelings and distrust logical analysis and abstract reasoning.
- **Independent knowing.** Most knowledge is uncertain. Students take responsibility for their own learning rather than relying heavily on authorities or personal feelings. They collect and use evidence to support judgments but tend to do so superficially, and they believe that when knowledge is uncertain all conclusions regarding it are equally good if the right procedure is used to reach them. In the *individual pattern* (more men than women), students rely on objective logic and critical thinking,

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challenging their own and others' positions to establish truth and make moral judgments. In the *interindividual pattern* (more women than men), students rely on caring, empathy, and understanding of others' positions as bases for judgments.

- **Contextual knowing.** All knowledge is contextual and individually constructed. Students take responsibility for making judgments, acknowledging the need to do so in the face of uncertainty and ambiguity. They use all possible sources of evidence in the process—objective analysis and intuition, their own thoughts and feelings and ideas of others whose expertise they acknowledge—and they remain open to changing their conclusions if new evidence is forthcoming.

The preceding paper in this series [2] compared this model with several other widely used models of intellectual development. The stages of Baxter Magolda's model parallel those of the King-Kitchener model of reflective judgment [3]; Baxter Magolda's male-dominant progression of stages and patterns parallels Levels 2–5 of Perry's Model of Intellectual Development [4]; and her female-dominant progression parallels a model formulated by Belenky *et al.* in *Women's Ways of Knowing* [5].

The intellectual curiosity, openness to alternative ideas, and acceptance of responsibility for one's own learning that characterize the highest levels of these models might stand as definitions of how expert scientists and engineers think, so that anything universities can do to promote intellectual development will help science and engineering schools and departments fulfill their educational mission. The purpose of this paper is to propose an instructional model for achieving that goal. While the paper can stand alone if necessary, it draws heavily on concepts defined and described in its companion article [2]. We encourage the reader who has not yet read that article to do so before proceeding with this one.

II. APPROACHES TO LEARNING AND ORIENTATIONS TO STUDYING

A concept closely related to intellectual development is that of *approaches to learning*. This section reviews this concept, shows that a deep approach to learning is almost by definition what students at high levels of intellectual development tend to practice, and summarizes the conditions that have been shown to promote adoption of a deep approach. The instructional model to be proposed incorporates these conditions.

Marton and Säljö [6] define two dramatically different approaches to learning—a *surface approach* and a *deep approach.* Students who take a surface approach memorize facts but do not try to fit them into a coherent body of knowledge and follow routine solution procedures without trying to understand their origins and limitations. These students commonly exhibit an extrinsic motivation to learn (*I've got to learn this to pass the course, to graduate, to get a good job*) and an unquestioning acceptance of everything in the textbook and in lectures. To them, studying means scouring their texts for worked-out examples that look almost identical to the homework problems so they can simply copy the solutions. They either ignore the text outside of the examples or they scan through it with a highlighter, looking for factual information that the instructor might consider important, which they will attempt to memorize before the exam. They often do poorly in school.

In contrast, students who take a deep approach try not just to learn facts but to understand what they mean and how they are related to one another and to the students' experience. They have an intrinsic motivation to learn the material and a tendency to question conclusions offered in lectures and readings. They cast a critical eye on each statement or formula or analytical procedure they encounter in class or in the text to see if it makes sense to them and do whatever they think might help them understand, such as restating text passages in their own words, thinking of analogies to things they know, or trying to come up with their own examples. Once the information makes sense, they try to fit it into a broad conceptual view of the subject or chapter rather than simply memorizing it if it looks like something that might show up on the exam.

A student may adopt different approaches to learning in different courses and even for different topics within a single course. An *orientation to studying* is a tendency to adopt one of the approaches in a wide range of situations and learning environments [7,8]. Students who habitually adopt a surface approach have a *reproducing orientation,* and those who usually adopt a deep approach have a *meaning orientation*.

Based on their definitions, levels of intellectual development and orientations to studying are clearly related. Students with a reproducing orientation tend to treat their instructors and texts as sources of facts to be memorized and procedures to be followed. They neither challenge nor attempt to understand the facts and procedures, and they resent instruction that calls on them to do either. This pattern of behavior might serve as a definition of Baxter Magolda's absolute knowing [1], King and Kitchener's early prereflective thinking [3], Perry's dualism [4], and Belenky's received knowledge [5]. In contrast, students with a meaning orientation to studying take primary responsibility for their own learning, are perfectly comfortable challenging assertions of authorities, use whatever means they can to achieve a deep understanding of material they have undertaken to learn, and always try to place new material in the context of what they already know. The parallels between this description and Baxter Magolda's contextual knowing, Perry's contextual relativism, Kitchener and King's reflective thinking, and Belenky's constructed knowing are striking. We therefore speculate that instructional environments that stimulate the adoption of a deep approach to learning should also promote intellectual growth.

Entwistle [7] and Ramsden [9] summarize the characteristics of teaching that have been shown by research to promote a deep approach.

- *Student-perceived relevance of the subject matter*. Unless they are heavily motivated by a need to earn high grades, most students will not struggle to achieve a deep understanding of material that they cannot readily connect to their interests and the problems they are likely to be called upon to solve as professionals.
- *Clear expectations, practice, and feedback.* Students are not born knowing how to analyze deeply, and little in their pre-college experience is likely to have fostered that ability. They will be unlikely to exhibit a deep approach unless they clearly understand the instructor's expectations of them and they are given ample opportunities for practice and constructive feedback on their initial attempts.
- *Appropriate tests.* Provided the preceding conditions have been met, all examinations should include some items that call for deep analysis. If the students know they will only get surface questions (closed-ended exercises that require only standard solution procedures), they will likely take a surface approach to learning the material.
- *Reasonable workload.* If students have to spend all their time and energy just keeping up, they will tend to fall back on a surface approach.
- *Choice over learning tasks.* Students are more likely to make the effort to take a deep approach if they feel that they have some decision-making autonomy in selecting learning tasks.

We will incorporate these conditions in the instructional model to be proposed.

III. INSTRUCTIONAL MODEL FOR PROMOTING INTELLECTUAL DEVELOPMENT

Table 1 lists instructional conditions that should provide the challenge and support needed to promote intellectual development and suggests steps instructors can take to achieve these conditions.

Table 1
Instructional Conditions that Facilitate Intellectual Growth

A. Variety and choice of learning tasks 1. Varied problem types 2. Varied levels of assignment definition and structure 3. Choice on assignments, tests, and grading policies
B. Explicit communication and explanation of expectations 1. Instructional objectives covering high-level tasks 2. Study guides and tests based on the objectives
C. Modeling, practice, and constructive feedback on high-level tasks 1. Assignment of relevant tasks and modeling of required procedures 2. Practice in assignments followed by inclusion of similar tasks on tests
D. A student-centered instructional environment 1. Inductive learning 2. Active and cooperative learning 3. Measures to defuse resistance to student-centered instruction
E. Respect for students at all levels of development 1. A sense of caring about students 2. Awareness of and respect for current levels of development while promoting higher levels

The remainder of the paper elaborates on these conditions and offers suggestions for achieving them.

A. Variety and Choice of Learning Tasks

Students in any class are likely to span a spectrum of levels of intellectual development, so that learning tasks suitable for one group may be inappropriate for another (too easy, too challenging, too heavily structured, too ambiguous,…). The only way to assure that all students are confronted with some tasks within their *zone of proximal development* (enough above their current level to challenge them but not far enough to intimidate or discourage them) is to provide a variety of tasks that collectively cover the full range of levels among them, and the provision of choice helps assure that students will not be forced to work exclusively at levels that are either too high or too low for their current level of development. Students are also more motivated to take a deep approach to their learning when they feel that they have some part in setting the agenda, a feeling supported by giving them some choice over learning tasks [7,9].

There are several ways to provide variety and choice in assignments:

1. Varied problem types.

Engineering and science problems come in a broad range of types. Some are closed-ended with one correct solution that it is the problem solver's job to find and verify, others are open-ended with multiple solutions that the problem solver must identify and possibly choose among; some are theoretical, others are more applied; some call for library or web-based research, some for creativity, some for verbal or graphic artistry, some for problem formulation or identification, and some for the type of critical thinking that defines the higher levels on all of the intellectual development scales surveyed in the preceding paper [2].

One of the conditions known to promote a deep approach to learning is student-perceived relevance of the subject matter. Assigned high-level problems are most effective if they relate to students' backgrounds, interests, concerns, and career goals. Moreover, having some of the problems involve socially important topics such as biomedicine, environmental science and technology, safety, and human factors engineering will increase their effectiveness for students who exhibit the more subjective, feeling-oriented patterns of Baxter Magolda's [1] and Belenky's [5] intellectual development models.

The following high-level tasks could be used in almost any science or engineering course.

- *Predicting outcomes.* Describe physical demonstrations or experiments and have students predict the outcomes, and then describe (or if possible, carry out) the demonstrations or experiments and show the outcomes. The best demonstrations are those that generate incorrect predictions resulting from common misconceptions. Once the students are given concrete evidence that their mental pictures are wrong, they are ready to learn how things really work, while as long as they maintain their misconceptions (which students tend to do with impressive tenacity), lectures are likely to have very little effect. McDermott [10] gives several examples of good prediction problems in the context of physics education.

- *Interpreting and modeling physical phenomena*. Provide data from a real or hypothetical experiment or describe a (preferably) familiar phenomenon—mist forming just above the surface of a pond, for example, or salt on a driveway retarding ice formation, or beans cooking for hours at a ski resort and still not being done—and call on students to explain the results in terms of course-related concepts. Guide the students in formulating and—if possible—testing alternative explanations. Have them go on to formulate a model of the process if the data are quantitative, or give them alternative models and have them determine the best one.

- *Generating ideas and brainstorming* (*creative thinking*). Use open-ended exercises to move students away from the idea that all questions have single answers and all problems have unique solutions. Describe process or product designs and ask the students to brainstorm as many possible flaws and potential failures as they can, giving credit for every idea regardless of how far-fetched it might be, and then have them prioritize their projected flaws in order of likelihood and justify their prioritization. Ask them to devise as many ways as they can think of to measure a system variable or physical property, giving double credit for any method that involves the use of a randomly chosen object, such as a hamburger [11,12].

- *Identifying problems and troubleshooting.* Describe a device, experiment, process, or manufacturing system that is not working properly and ask the students to speculate on possible causes of the problem; then have them devise experimental tests that would confirm or refute their speculations.

- *Formulating procedures for solving complex problems*. Give incompletely specified problems and have the students itemize what they know and what they need to know, then determine how they will determine those unknowns (look them up, calculate them, measure them, estimate them from empirical correlations or rules of thumb,…). Problem-based learning [13–17] by definition involves exercises of this sort.

- *Formulating problems.* Ask students to make up problems having to do with the course content of the previous three weeks, then to make up and solve such problems, then to make up and solve problems having to do with both this course and another course in the curriculum. Specify that straightforward "Given this, calculate that" problems will either be unacceptable or worth a minimal passing grade, and that to earn a good grade the problems must require high-level skills (complex analysis, critical or creative thinking) [11,18].

- *Making judgments and decisions and justifying them* (*critical thinking*). Call on the students to make and support judgments on ambiguous or controversial matters. The problems discussed previously involving alternative explanations of observed phenomena or experimental results fall into this category. Students might also be called upon to reflect on the validity of editorials and articles in the popular press on science-related subjects; government policies on matters related to health and safety, alternative energy sources, and the environment; and dilemmas involving workplace safety and ethics. They should be told that they will not be judged based on their conclusion but on the quality of the evidence and reasoning they can muster to support it or the quality of their plan for gathering the evidence. Potential data sources should include observation, experimentation, published information, and information provided by both authorities and peers. The students should be taught to evaluate the reliability of the data sources and the validity and relevance of the data, to make interpretive judgments based on the data that survive this filtering, and to justify their judgments in concise and persuasive written and/or oral presentations.

Including a variety of problem types in assignments serves an important purpose besides promoting intellectual growth and adoption of a deep approach to learning. Some students are gifted in ways that may not show up on straightforward homework problems. If they are assigned problems that call for different skills, they sometimes discover talents they may not have known they possessed. The effect of this discovery on their self-confidence and subsequent performance levels—even on more conventional problems—can be dramatic.

2. Varied levels of assignment definition and structure.

At one extreme, assignments may be self-contained and unambiguous. Problems in such assignments have one and only one correct solution and the information needed to solve them is provided explicitly in the problem statement, and laboratory experiments are of the "cookbook" type, with the required experimental and data analysis procedures spelled out in complete detail. At the other extreme, assignments may be open-ended (with a range of possible acceptable solutions) and/or ill-defined (extraneous data is provided, or insufficient data is provided and part of the student's task is to identify what is missing and possibly to determine and substitute values), and the information and methods needed to complete the assignment are not limited to material in the course notes and text. Assignments may fall anywhere on the continuum between these two extremes.

Ambiguous and poorly structured problems are likely to be discomforting and/or incomprehensible to students at Baxter Magolda's levels of received knowledge (Perry Level 2) and subjective knowledge (Perry Level 3). To avoid overwhelming these students with material far removed from their zone of proximal development, instructors should only include a small number of such problems early in the curriculum, providing a great deal of guidance on how to solve them and having them count relatively little toward the final course grade. As the students advance in the curriculum, the percentage of such problems should increase and there should be a fairly healthy dose of them in the senior year, with reasonable performance on them required to earn high course grades.

3. Choice on assignments, tests, and grading policies

Providing some choice over learning tasks has been shown to correlate with adoption of a deep approach to learning [7,9] and so promotes intellectual growth. Students may be given some latitude in selecting from among alternative assignments (e.g., either homework and an exam or an independent project); alternative problems on assignments and exams (solve Problem 1 and any 3 of Problems 2–5); and deciding in advance—individually or collectively—how their grades on assignments, midterm exams, and the final exam should be weighted to determine their course grades.

B. Explicit Communication and Explanation of Expectations

1. Instructional objectives covering high-level tasks

When students at low development levels are confronted with high-level tasks, a major barrier to their success is a lack of understanding of exactly what they are being asked to do. To lower this barrier, instructors should formulate explicit *instructional objectives* (aka *learning objectives*) that involve a broad spectrum of critical thinking and problem-solving skills and decision-making strategies, communicate those objectives to the students, and be clear about their purpose.

Instructional objectives are statements of observable actions or behaviors that demonstrate students' knowledge, understanding, abilities, or attitudes [19,20]. They normally take one of the following forms:

Upon successfully completing this [course, chapter in the text, week,…] *the student will be able to…*

On the next test, you may be called upon to…

What follows either stem is an action the students might be asked to carry out to demonstrate their mastery of the knowledge and skills they are expected to acquire. The action may involve cognition (*list, explain, calculate, classify, derive, design, model, select and justify,…*) at levels of thinking that range from pure memorization to complex analysis, creative thinking, and critical thinking [21,22], or it may relate to a psychomotor activity (e.g., carry out a laboratory procedure, operate or repair an instrument or machine,…) [23] or to a behavior that reflects a specified attitude or value (e.g., ethical behavior or teamwork or intellectual curiosity or tolerance of diversity) [22,24]. The formulation of instructional objectives corresponding to the full range of required attributes of engineering graduates defined by the U.S. Accreditation Board for Engineering and Technology is discussed by Felder and Brent [25] and by Besterfield-Sacre *et al.* [26].

The following cognitive tasks might be included in instructional objectives for a course designed to promote intellectual growth:

- *Explain familiar phenomena involving heating and cooling of objects and perceptions of hotness and coldness (for example, the fact that you feel warm in 20°C air and cold in 20°C water) in terms of concepts discussed in this course.*
- *Given data from an experiment designed to measure a physical property of a material, (a) estimate the property and the 95% confidence limits for your estimate, (b) explain the significance of the confidence limits in terms that someone who has no knowledge of statistics might understand, (c) suggest at least ten reasons why your estimate might be much different from a value of the property found in a published article or a standard reference such as the* Handbook of Chemistry and Physics, *including in your list at least five assumptions you made in your data analysis that might not be valid.*
- *Identify the potential risks in a described experiment that involves a hazardous substance or operation, formulate a detailed experimental procedure to minimize the risks, and specify provisions you would make to deal with possible emergencies.*
- *Critique the scientific validity of a short article or opinion column in the popular press that involves topics related to this course, pointing out specific instances of errors, unstated or unsupported assumptions, and sloppy reasoning. Outline the research you might carry out to reach a supportable conclusion about the issue being addressed by the article, detailing the information you would seek and outlining how you would gather it.*
- *Make up and solve a homework problem that involves the material covered in this course this week and material from at least one other course you are taking this semester. The problem solution should require critical thinking and/or creative thinking on the part of the problem solver*. (See Felder [18] for examples of student responses to an assignment of this sort.)

- *Given a complex problem, state the major principles and outline the strategy to be used for the solution. Do no derivations or calculations.*

The last of these objectives is suggested by the work of Bransford *et al.* [27] summarizing research on the differences between expert and novice problem solvers. Experts generally begin by categorizing the problems in terms of applicable principles and general procedures, while novices immediately start looking for information they can copy from their text or notes and specific equations they can substitute numbers into. Leonard *et al.* [28] routinely had their introductory physics students identify principles and outline solution strategies before doing any calculations, and found that the students performed significantly better on problem categorization tasks than students who took a traditionally-taught course did.

2. Study guides and tests based on the objectives

Instructional objectives are most effectively communicated to students as study guides for examinations. Students are likely to ignore a long list of objectives handed out at the beginning of the course but they will pay attention to a list of things they might be asked to do on a forthcoming test, and they will be particularly attentive after the first test if the instructor can show that every test question was previewed somewhere on the study guide. Among other benefits of this approach, the instructor will never again have to deal with the dreaded "Are we responsible for this on the test?" The answer is, "If it's on the study guide, you are."

A technique that addresses the diversity of intellectual levels in a class is to specify that certain high-level questions on the study guide will account for a specified percentage of the total point value of the test. These would be the questions that would be comfortable for students at the contextual knowledge level, would represent challenges to independent knowers, and might be out of reach for absolute and transitional knowers, who tend to take a surface approach to learning. The instructor should not bill these as "extra credit" or "bonus" questions, since it should be clear that such skills are needed in science and engineering and all students should work as hard as possible to acquire them. How much they should account for is up to the instructor: a reasonable rule of thumb is 10–15% for introductory courses, and higher percentages for upper-level courses provided that instruction and practice in high-level tasks has been consistently provided throughout the curriculum.

C. Modeling, Practice, and Constructive Feedback on High-Level Tasks

Students preparing for careers in technical fields should be quickly disabused of the notion that scientists and engineers work mostly on problems that can be solved using memorized facts and procedures. The instructor should persuade the students that they will need to think independently as professionals, give examples of the kinds of problems they are likely to encounter in both practice and research, acknowledge that some of those problems may initially make them uncomfortable, and promise them that they'll get lots of coaching before they are tested on similar problems.

Then the promise should be kept. People acquire complex skills—physical and mental—through practice and feedback and in no other manner, and practice and feedback are among the conditions known to promote a deep approach to learning. It follows that promoting the thinking, problem-solving, and decision-making skills that characterize high levels of development will require providing extensive practice and feedback on tasks that require those skills—in the terminology of Fink [22], providing *significant learning experiences*. Feedback may be provided externally or it may involve self-reflection on the outcomes of prior efforts.

1. Assignment of relevant tasks and modeling of required procedures

Once the types of tasks that demonstrate high levels of intellectual development have been defined in instructional objectives, tasks of each type should be assigned repeatedly as in-class exercises and homework problems. Instructors should realize, however, that the reasoning processes and confidence levels needed to solve such problems are likely to be lacking in students at the lower range of the intellectual development spectrum, so that those students are unlikely to understand what they are being asked to do. Explicit modeling of the required methods is needed initially to provide clarification.

The least effective way of modeling thinking and problem-solving processes—and unfortunately, the only way generally used in traditional instruction—is to transcribe fully worked-out examples on a whiteboard or overhead projector, or worse, to show the examples on pre-prepared transparencies or in a PowerPoint show. For example, a traditional instructor teaching students to analyze complex fluid dynamical systems would derive the appropriate conservation law equations, supply boundary conditions, make simplifying approximations, and solve the resulting equations. The assumption is that once students watch someone doing all that they will understand the reasoning processes that underlie each step and should be able to do it themselves on assignments and tests, an assumption abundantly contradicted by every instructor's experience as well as by cognition theory. The same criticism applies to simply showing worked-out solutions to open-ended problems, ill-structured problems, ethical dilemmas, or any of the other types of problems that require high-level thinking skills.

An explicit goal of instruction intended to promote intellectual growth should be to demystify authority [1]—to move toward using dialogue and discovery as vehicles for learning, rather than simply providing expertise. The approach just described, in which an instructor lays out perfectly constructed solutions to complex problems, has the opposite effect. A better way is to work through the solutions the way the students would have to, thinking aloud so that the students can follow the details. The students would then see and hear how they should approach problems—contemplating alternative procedures, choosing one, hitting dead ends and retreating and restarting in new directions, running checks to validate intermediate results, and finally reaching the desired result and verifying it in every way possible.

Still greater learning will occur if the students—working individually or in small groups—are given brief opportunities to figure out what to do next at several points in a worked-out example. If they succeed, they own that part of the solution; if they struggle for a few minutes and fail, they will be in a much better position to understand when the instructor does it than they would have been without the active involvement. Felder and Brent [29] offer tips for devising such active learning exercises and making them effective, and Felder [30] provides a detailed example of such an active learning process in the context of a course on chemical process principles.

A defining feature of advanced intellectual development is the recognition that not all problems have unique solutions. Another good form of modeling is to offer several alternative acceptable solutions to an open-ended problem, noting that despite their differences they would all receive equally high grades. The solutions might be generated by the instructor, or they may be taken from students' solutions from previous offerings of the course.

Perhaps the best learning experience students can have is actually to work in the environment for which their education is preparing them, such as a cooperative education (co-op) placement or summer internship in industry. Wise *et al.* [31] have speculated that such an experience should have a positive effect on students' developmental levels, and Palmer and Marra [32] note that some students who exhibited the highest proposed orientation to science (which resembles contextual relativism) cited their real-world experiences as having significantly influenced them. As one of those students said,

> *You might be asked to work on a project and you have to explore the different views of the consumer or of the product. It's different than in a classroom where you're given a problem and the professor knows the answer. There is one answer and he assumes there*

is one approach because he knows. He's worked out the problem and the theory is all there. But it gets a lot more complex when you go into industry.

A research study to test the hypothesis that co-op experiences and internships promote intellectual development would be well worth conducting.

2. Practice in assignments followed by inclusion of similar tasks on tests

After modeling solution procedures, instructors should give repeated practice in high-level tasks in class and on homework, and after this has been done (and *only* after it has been done), include such tasks on tests. It makes little sense to put a high-level problem with an unfamiliar twist on a time-limited test "to see if the students can think for themselves," when the students have not been given adequate modeling, practice, and feedback beforehand. No research has ever shown that the ability to solve intellectual puzzles in brief periods of time (for that is what such problems are) correlates in any way with scientific ability or achievement, and testing students on high-level skills that have not been taught is arguably unethical. On the other hand, if high-level tasks are included in instructional objectives and the required skills are taught but the tasks are never included on tests (or other performance assessments that count toward the final course grade), only the few students in the class with a meaning orientation to studying will make a serious effort to acquire the skills.

D. A Student-Centered Instructional Environment

Perhaps the single most identifiable characteristic of intellectual growth is a decreasing reliance on authority for the answers to all questions, and so instruction intended to promote intellectual growth should have that as one of its principal goals. It can be achieved by using *student-centered instruction*, a general term for any approach that requires students working individually and in groups to take much more responsibility for their learning than the traditional lecture-based approach requires. In the well known phrase from the cooperative learning literature, the instructor moves from being the "sage on the stage" to becoming the "guide on the side."

In traditional instruction, the teacher's primary functions are lecturing, designing assignments and tests, and grading; in student-centered instruction, the teacher still has these functions but also provides students with opportunities to learn independently and from one another and coaches them in the skills they need to do so effectively. In recent decades, the education literature has outlined a wide variety of student-centered instructional methods, including having students confront problems before they are given all the material needed to solve them (*inductive learning*), replacing some lecturing with participatory exercises done by individuals or small groups in class (*active learning*), and having students completing assignments in teams under conditions that assure individual accountability for all the work (*cooperative learning*). Extensive research has demonstrated that when properly implemented, these approaches lead to increased motivation to learn, greater retention of knowledge, deeper understanding, and more positive attitudes toward the subject being taught [27,33–40] and to the development of more complex views of the nature of scientific knowledge [32,41,42].

1. Inductive learning

The traditional approach to both course and curriculum design in science and engineering is deductive, beginning with "fundamentals"—theories and basic principles, derivations of formulas and mathematical algorithms—and subsequently presenting the applications that make use of the fundamentals. In many freshman science courses (e.g., chemistry courses that launch the students directly into molecular modeling) and early engineering courses (e.g., introductory fluid dynamics courses that start with momentum balances on differential fluid elements and perhaps even stress tensors), instructors present new material without relating it to things the students already know about from their own experience or from prior courses, and without previewing how it will be needed to solve problems 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"). This approach has repeatedly been associated with low motivation, poor learning, negative attitudes toward the subject, and high student attrition [43]. The fact that many students in courses taught this way appear apathetic and do poorly is a common source of frustration to the instructors, but it should not come as a surprise.

Unless they are heavily motivated by a need to earn high grades, most students will not struggle to achieve a deep understanding of material that seems pointless to them. To motivate them to make the effort, instructors should tell them up front what the material has to do with their everyday lives (e.g. fluid flow in their cars and circulatory systems, heat and mass transfer and reaction in the atmosphere and their homes and their respiratory and digestive systems) and with significant problems they will eventually be called on to solve (e.g. fabricating improved semiconductors, developing alternative energy sources, avoiding future Bhopals and Chernobyls). Virtually all modern research-based references on effective teaching and learning agree that students tend to study hardest and learn best what they are interested in and believe they have a need to know [9,27,44–46].

An effective way to motivate a desire to learn a topic is to introduce it in terms of specifics (facts, familiar phenomena, real problems) and to bring in abstract concepts, principles, and theories only after a need to know them has been established in the context of the specifics. Since in logic a flow of reasoning from the specific to the general is labeled induction, instruction of this nature may be termed *inductive learning*. Variants of this approach include *problem-based learning*, *project-based learning*, *guided inquiry*, *discovery learning*, and *just-in-time teaching* [13–17]. In all of these methods, students are confronted with questions, problems, or project assignments, work (frequently in teams) to clarify and define the questions and determine what they need to know to complete the assignments, and are taught or guided to teach themselves course material after they clearly perceive the need for it in the context of the task they are attempting to complete.

If students view knowledge as abstract and unconnected to the world of their experience, they are likely to have trouble relinquishing their misconceptions. Establishing the practical relevance of all course material to their existing knowledge base, interests, and career objectives legitimizes their knowledge as a foundation for constructing new knowledge. Besides the fact that they learn better this way, this approach pushes them toward the independence and ability to cope with ambiguity and open-endedness that characterize high levels of intellectual development.

An example of the use of an inductive approach in an engineering curriculum is provided by Wise *et al.* [31], who report on the introduction of hands-on team projects in a first-year design course. The gain in average Perry rating of the students who completed this course was statistically significantly higher than the average gain of a control group that had not. The effect did not persist at a statistically significant level in the remainder of the curriculum. The loss of significance may be attributable in part to a sharp reduction in the sample size of the experimental group past the first year, and it may also reflect the failure of the subsequent curriculum to provide the balance of challenge and support that leads to growth.

2. Active and cooperative learning

Active learning generally refers to in-class instruction that involves students working individually or in small groups on tasks related to the course instructional objectives—answering questions, solving problems or parts of problems, troubleshooting, brainstorming, and in general doing anything but watching a lecture. The positive effects on knowledge and skill acquisition of interspersing brief active learning exercises in a lecture class are well established [27,33,36–38], and techniques for incorporating active learning in science and engineering courses have been described in several references [29,30,47–51].

The power of groupwork in learning and skill development has also been conclusively demonstrated [27,34–36,39,40]. In a famous quote, Wilbert McKeachie, author of the classic reference *Teaching Tips* [36], said

> *The best answer to the question, "What is the most effective method of teaching?" is that it depends on the goal, the student, the content, and the teacher. But the next best answer is, "Students teaching other students."*

A cooperative learning (CL) model formulated by David and Roger Johnson and applied to engineering education by Karl Smith [34] is particularly suitable for addressing the learning needs of students across the spectrum of levels of intellectual development. According to this model, CL consists of students working in teams on structured assignments (homework or projects) under conditions that meet five criteria:

- *Positive interdependence***.** The team members must rely on one another to accomplish the goal.
- *Individual accountability*. Each team member is held accountable for doing his or her share of the work and for all of the material in the assignment, regardless of who was principally responsible for it.
- *Face-to-face interaction, at least part of the time***.** Some or all of work must be done by members working together (as opposed to parceling out the assignment to individual members and putting the completed pieces together without discussion).
- *Appropriate use of interpersonal skills.* Team members must practice and receive instruction in leadership, decision-making, communication, conflict management, and other critical teamwork skills.
- *Regular self-assessment of group functioning.* The team members periodically reflect on what they are doing well as a team, what they could improve, and what (if anything) they will do differently in the future.

The literature describes how these conditions can be achieved [34,52,53] and how the appropriate use of cooperative learning can address all of the outcomes specified in the ABET engineering program accreditation criteria [25].

3. Measures to defuse resistance to student-centered instruction

While the learning benefits of active and cooperative learning and inductive methods such as problem-based learning have been demonstrated in hundreds of studies, instructors who use those methods cannot count on getting a warm and enthusiastic reception from all of the students. While some students respond well to open-ended questions and group work, others express unhappiness or outright hostility toward them. They may grumble that the teacher is supposed to tell them what they're supposed to know rather than making them figure it all out themselves, and they may call his or her knowledge of the subject and/or competence as a teacher into question. Instructors who are not prepared for this resistance often find it overwhelming when they first encounter it, and some become discouraged enough to go back to less effective teacher-centered instruction rather than trying to overcome the resistance.

The first step in defusing and overcoming student resistance to student-centered instruction is to understand it. Felder and Brent [54] have written in general terms about the nature and causes of the resistance and have suggested ways that instructors can deal with it effectively when it appears. It is vitally important, for example, to explain to the students at the outset what nontraditional teaching methods (active learning, cooperative learning, problem-based learning,…) will be used in the class and why the instructor has chosen to use them. The students might be informed that working in teams to solve real-world problems is exactly what most of them will do as professionals, and so learning how to do it is an essential part of their professional training. Moreover, extensive research demonstrates that students taught with cooperative learning methods on average outperform students taught in traditional lecture-intensive classes in almost every conceivable learning outcome. The references cited in the previous section can be used to support the latter claim if students ask for proof (which they rarely do). For additional strategies, see Reference 54.

Felder [55] and Marra and Palmer [56] have discussed and presented vignettes illustrating how students' attitudes toward student-centered learning are likely to depend on their level of intellectual development according to the Perry model—in particular, on how they view instructors and peers as sources of truth. Baxter Magolda's model offers valuable insights regarding that issue. Based on her definitions (summarized in Reference 2), we speculate that the attitudes listed below would characterize students at different levels. To the extent that they do, being aware of levels of intellectual development can help an instructor help students through whatever difficulties they may be experiencing with a student-centered instructional approach.

- *Absolute knowers* are likely to be negative about student-centered methods, since they regard instructors as the only legitimate sources of information and lectures as the only legitimate form of transmitting the information. Those in the mastery pattern (Perry's dualists) are almost certain to be hostile to all student-centered methods and to be in conflict with teammates in cooperative learning groups who attempt to defend those methods, while those in the receiving pattern value the mutual sharing and support of peers and so should be less resistant to cooperative learning (but still strongly opposed to inductive approaches like inquiry and problem-based learning).

- *Transitional knowers* no longer believe that authorities have a monopoly on truth, and so they are less likely than absolute knowers to be hostile to any form of student-centered learning. If they are in the impersonal pattern, they accept the role of instructors in teaching them how to find answers and solutions, and if that means problem-based and cooperative learning, so be it. In cooperative learning, however, they may have little patience with teammates who do not appear to be making valuable contributions, and they are likely to resent being evaluated for anything as subjective as their performance as team members. Students in the interpersonal pattern place a great value on rapport and so will generally be particularly receptive to cooperative learning, but since they believe that their own personal judgment should determine truth for them they may resist the need for teams to reach consensus on the correct solution to problems, and they may be particularly critical of teammates who try to make logical analysis the only acceptable problem-solving approach.

- *Independent knowers* believe that they are primarily responsible for their own learning and so are likely to be receptive to student-centered methods and to value instructors who use them. They believe that they should receive high marks for following the correct procedure, however, and so may resent being downgraded for the quality of their reasoning in open-ended problems or for their poor teamwork skills. If they are in the individual pattern, they tend to be adversarial and reluctant to compromise in their attempts to determine truth and so may be in perpetual conflict with teammates. Students in the interindividual pattern, on the other hand, value relationships above all, listen carefully to others, and make every attempt to understand them and to try to take their viewpoints into account. They may be very highly regarded by their teammates, but if they are surrounded by students who are primarily absolute knowers (and so hostile to student-centered methods) or who fall into the impersonal pattern of transitional knowing or the individual pattern of independent knowing, they are likely to become alienated and withdraw from full participation in the group. This is one justification for the suggestion in many references on cooperative learning to avoid groups in which women (who are more likely than men to fall into the interindividual category) are isolated.

- *Contextual knowers* are likely to be far more open to student-centered methods than to more traditional teacher-centered instruction, and given their relative sophistication in the use of evidence-based reasoning they should do extremely well with those methods. Like their independent knowing counterparts in the interindividual pattern, their good listening skills and inclination to value the contributions of their peers make it probable that they will be valuable and valued team members in cooperative learning. If they have a problem, it is likely to be impatience with teammates at lower levels, who are either hostile to student-centered methods on principle (absolute knowers) or whose lack of skill at making evidence-based judgments leads them to jump to conclusions prematurely and incorrectly (transitional and independent knowers).

Given these widely disparate attitudes among students toward nontraditional instruction and the great potential for conflict between students at different levels forced to work together in cooperative teams, instructors might wonder why they should use student-centered methods in heterogeneous classes. There are several reasons. The first is that the methods work: the research is clear that when properly implemented, they lead to better learning, longer retention, greater skill development, and higher self-confidence for most students relative to more traditional teacher-centered methods [27, 33–40]. Second, when students enter a profession, they will inevitably encounter the same variations in intellectual development among their colleagues that they experienced in school, and their job performance evaluation may depend more on how well they can manage to work with those colleagues than on their technical skills. Helping them learn to do it could be one of the most important functions of their education. Finally, students at different intellectual levels can be *taught* to work together effectively, and in fact, a substantial portion of the cooperative learning literature offers guidance on helping dysfunctional teams (which teams composed of students at different levels often are) get past their difficulties [52,53,57].

E. Respect for Students at All Levels of Development

The steps recommended so far for pushing students to higher levels of intellectual development are almost certain to make many of them uncomfortable. Indeed, if they are not confronted by situations that force them out of their comfort zones, either they will not advance to higher intellectual levels or any changes that do occur will be superficial and transient. While some discomfort is thus expected and desirable when intellectual growth is promoted, if it is too great the students are likely to react by becoming overtly hostile or simply closing their minds to whatever ideas and attitudes the instruction is intended to promote.

There are several ways to keep students' discomfort from getting out of hand, including some of the previous suggestions. Varying the types of problems and projects assigned and providing some degree of choice helps assure that students are not always being forced outside their zones of proximal development; modeling and providing extensive practice in the types of thinking sought helps build their confidence that they are capable of doing what they are being asked to do; and using the recommended techniques to minimize or overcome student resistance to nontraditional instruction reduces the likelihood of temporizing and retreat. For students having a particularly hard time making the adjustments to higher-level thinking, supplementary individual support during office conferences can be helpful, as can complimentary affirmations when evidence of growth is seen.

Perhaps the most important thing an instructor can do to promote intellectual growth, however, is to make students believe that they are respected for who they are and safe in moving into uncharted and possibly threatening waters. As was noted in the companion article to this one [2], an accepting and supportive classroom environment has been found to enhance both academic achievement and intellectual development [58,59]. Instructors can do several things to establish such an environment.

1. A sense of caring about students

The importance of caring may be the most commonly agreed-upon point among experts on teaching effectiveness. Paul Ramsden [9] states that consciousness of and consideration for students are qualities that are "mandatory for every good teacher." Joseph Lowman [60] considers interpersonal rapport with students one of the two components of his model of effective teaching (the other component being intellectual excitement), and does much in his popular book *Mastering the Techniques of Teaching* to establish the links between students' sense of being respected and their motivation to learn. In his massive study of factors influencing student success, *What Matters in College* [61], Alexander Astin found that the quality of student-faculty interactions (as measured by the frequency with which students talk with professors outside class, work with them on research projects, assist them in teaching, and visit their homes) correlates with student grade-point average, degree attainment, enrollment in graduate or professional school, every self-reported area of intellectual and personal growth, satisfaction with quality of instruction, and likelihood of choosing a career in college teaching.

According to Lowman [60], learning names is "the single most important thing a college teacher can do to communicate to students that he or she values them as individuals." A variety of name-learning strategies have been devised, including making and studying labeled photographs, seating charts, index cards with identifying characteristics and selected personal information, and photocopies of ID cards. Other ways of establishing rapport with students include giving them a voice in establishing class policies and procedures, soliciting their recommendations for change (e.g., in minute papers and midsemester evaluations) and responding to the recommendations in as positive a manner as possible, and doing anything that provides what Kenneth Eble calls "excuses and opportunities for easy talk" [62] such as coming to class early and staying afterwards, being available and fully present during office hours and individual conferences with students, and showing up occasionally in the student lounge (and perhaps holding office hours there).

Finally, caring requires an instructor to acknowledge that students have many demands on their time besides the course that he or she happens to be teaching—other courses, jobs, extracurricular activities, and family responsibilities, among other things. The deep approach to learning that characterizes high levels of development takes time. If the course assignments violate the rule-of-thumb of two hours outside class for every hour of class, the students are likely to revert to a low-level surface approach as a means of survival [6,7,9].

2. Awareness of and respect for current levels of development while promoting higher levels

The remarks students make in class, in conferences, and in casual conversation, and the ways they approach assignments can convey much about their viewpoints and assumptions about knowledge and the roles of instructors and students in its acquisition. Absolute and early transitional knowers tend to reveal themselves by complaining about teaching that goes beyond straight lecturing, assignments that call for more than memorization and repetition, and grading that involves anything but purely objective determination of the correctness of their facts and calculated values. Late transitional knowers and independent knowers often give themselves away by using evidence superficially in making decisions, prematurely jumping to conclusions, and complaining when they are not given full credit for their work even though their results are incorrect. It is easy and tempting for an instructor to disparage these behaviors, but counterproductive to do so if the goal is to help the students grow out of them. Eble [62] observes that "If we want students to respect learning, we must respect their efforts, however ill-informed and unsophisticated they may seem. We must respect *them*, not for what they will be when we get through with them, but as they are now."

Before doing any challenging or correcting, the instructor should make every effort to ascertain and respectfully acknowledge the students' positions on the issues in question. If this is not done, the students are apt to stiffen their resistance to any challenges to their ideas. The instructor might then gently remind the students that his or her responsibility is to prepare them for the conditions under which they will be working as professionals. The absolute and transitional knowers might be told that as scientists and engineers, they will not just be given well-defined problems that can be answered simply by looking up facts, plugging numbers into formulas, and carrying out straightforward experimental and computational procedures. The problems they confront will often be messy and poorly defined, and they will not be able to rely on lecture notes, instructors' assistance during office hours, and worked-out solutions from previous semesters. The independent knowers might be told that as professionals, they will be judged entirely on the correctness of their results and not on how hard they worked or whether or not they followed the right procedure. Since working under those conditions is what they will have to do after graduation, the instructor's responsibility is to do everything possible to help them learn to do it while they're still in school, and that is exactly what the assignments they are having difficulties with are designed to do.

The tone of such interactions with students may be as important as the content of the interactions, which is a message that many science and engineering instructors find difficult to absorb. Regardless of their developmental levels and patterns of behavior, students are unlikely to respond positively to logic-based challenges to their world-views unless they first believe that they have been heard and understood. Moreover, if challenges to their ideas are presented in purely objective and non-supportive terms or if the instructor appears intimidating or disrespectful, the students whose mode of learning relies heavily on rapport with others (those in the receiving pattern of absolute knowing, the interpersonal pattern of transitional knowing, and the interindividual pattern of independent knowing) are likely to reject current and future challenges and to avoid any further interaction with the instructor.

Instructors can put students at their ease in individual conferences in a variety of ways, including expressing appreciation of the students' taking the time to see them, maintaining eye contact, sitting next to the students rather than across a desk from them, ignoring interruptions such as phone calls or other would-be visitors, listening carefully, and avoiding overtly defensive, judgmental, inquisitional, or hostile responses. Some instructors instinctively avoid such responses; for others, it may take considerable conscious effort to do so, but it is an effort well worth making.

IV. SUMMARY

Most college students undergo a developmental progression from a belief in the certainty of knowledge and the omniscience of authorities to an acknowledgment of the uncertainty and contextual nature of knowledge, acceptance of personal responsibility for determining truth, inclination and ability to gather supporting evidence for judgments, and openness to change if new evidence is forthcoming. At the highest developmental level normally seen in college students, individuals display thinking patterns resembling those of expert scientists and engineers. Unfortunately, most science and engineering students enter college at low levels, and when they are taught traditionally they generally graduate at levels not much higher than those at which they entered.

A necessary condition for a student's intellectual growth is *challenge* to the beliefs that characterize his or her current level. Students who believe that all knowledge is certain and all problems have solutions must be challenged with issues that cannot be neatly resolved and open-ended problems that have many possible acceptable solutions. Those who think authorities are omniscient and infallible must be made aware that experts—including their instructors—make mistakes, cannot solve all problems, and frequently disagree with one another. Those who believe that when knowledge is not certain all opinions are equally valid must be challenged to provide evidence to support their judgments and should be evaluated based on the quality of the evidence they provide. Challenge is not enough, however:

students confronted with challenges to their basic beliefs may feel threatened and either persist at their current developmental levels or retreat to even lower levels. To avoid these outcomes, appropriate emotional *support* for students should accompany challenges to their beliefs.

To provide a balance of challenge and support suitable for promoting the intellectual development of their students, instructors should adopt an approach to teaching that has the following five features:

1. **Variety and choice of learning tasks**. Different learning tasks are suitable for students at different levels. Assigning tasks that cover the full developmental spectrum assures that each student will be appropriately challenged at least some of the time. Assignments should vary in type (closed- and open-ended problems, straightforward problems and problems that call for creative and/or critical thinking) and level of structure (well-defined problems and incompletely or ambiguously defined problems). Making the exercises as relevant as possible to students' backgrounds, interests, concerns, and career goals helps motivate the students to take them seriously, and providing some choice in the assignments helps minimize the frequency at which students are forced to work at levels too high or too low for their current level of development.

2. **Explicit communication and explanation of expectations**. The better the students know and understand what they are expected to do, the greater the likelihood that those with the necessary aptitude will end by being able to do it. Instructors can clarify their expectations by writing instructional objectives (explicit statements of the things the students will be expected to do to demonstrate their mastery of the course content) and sharing them with the students. The most effective way to share objectives is to hand them out as study guides for examinations and other learning assessments and then include a representative subset of the objectives in the assessments. High-level objectives might account for roughly 10–15% of the total point value in introductory courses, with the value increasing in upper-level courses provided that appropriate instruction and practice in high-level tasks has been provided throughout the curriculum. If the high-level objectives are clearly linked to the assessment in this manner, most students will pay attention to them and do their best to prepare to meet them.

3. **Modeling, practice, and constructive feedback on high-level tasks**. When high-level problems are to be assigned, the instructor should model in class the types of thinking expected from the students and give the students practice exercises of the same type in class and in assignments. To equip students with mastery of a high-level skill by graduation, modeling, practice, and feedback in that skill should begin in the freshman year and should become more frequent as the curriculum advances. Once the instruction has been provided in a course, the skill should be included in the learning assessment done for the course and the students' mastery of the skill should count toward the course grade, if only by a token amount. The assessment drives the learning.

4. **A student-centered instructional environment.** Requiring students to take more responsibility for their own learning—which is to say, using student-centered instruction—promotes the decreasing reliance on authorities that characterizes intellectual development. An effective way to do so is to use an inductive learning approach: present observations and experimental data and help students formulate models and infer underlying principles and theories, and present fundamental material (math, basic science) only after a need to know it has been established in the context of realistic and complex problems. Examples of this approach include *problem-based learning, project-based learning, guided inquiry*, and *just-in-time teaching*. Other effective student-centered approaches include *active learning*, in which lectures are partially replaced with course-related activities during class, and *cooperative learning*, in which students work on assignments and projects in teams under conditions that assure (among other things) individual accountability for all the learning supposed to

take place. The learning benefits of these approaches, including their role in helping students acquire and improve higher-level thinking and problem-solving skills, have been well established by research.

5. **An attitude of respect and caring for students at all levels of development.** Asking students to change their fundamental beliefs about their role in constructing knowledge and making evidence-based judgments is asking a lot of them. Unless instructors augment their challenges to students' beliefs with measures to convey a sense that they care about the students and are willing to help them meet the challenges, the students are likely to feel threatened and stiffen their resistance to change. Some supportive measures are embedded in the previous conditions, including modeling and giving extensive practice in the desired types of thinking and providing some choice in assignments, but even more important is establishing an atmosphere of respect and caring. Ways of doing so include learning students' names, soliciting their viewpoints regarding class policies and procedures and being open to their ideas, setting up opportunities for student-faculty interactions in and out of class, and being fully present with them during interactions that may arise. Also, challenging students to adopt the thinking patterns of higher developmental levels should be justified on the basis that doing so will be essential for the students' professional success, and not because the lower levels are somehow inferior. Most studies of teaching effectiveness agree that students' perception of an instructor's respect and caring is a vital factor in promoting every conceivable measure of student achievement, self-confidence, and satisfaction. A single supportive instructor can play a major role in facilitating intellectual growth and may well make the difference between success and failure in a course and between staying in science or engineering and dropping out.

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