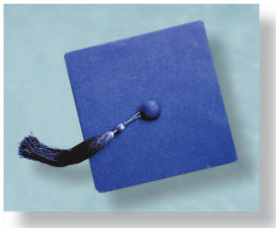

Educator's Corner

Framing Questions to Attain Higher Educational Objectives

■ **Madhu S. Gupta**

The principal purpose of this article is to help engineering teachers improve the exercises and problems they use in classroom activities, homework assignments, and tests, and which are the dominant learning vehicles in much of engineering education. The intimate relationship between classroom problems and educational objectives is elucidated through the recently revised Bloom's taxonomy of cognitive skills, which organizes the learners' abilities in a hierarchy with six major categories and emphasizes the importance of attaining the higher-level abilities. The selection and construction of problems to reach a wider set of educational objectives is described in detail and illustrated through problems taken from the topic of noise figure of cascaded linear two-port networks to demonstrate how different cognitive abilities can be exercised within the same subject matter.

It is common for instructors, desirous of improving their instruction, to devote much of their attention and efforts to their in-class activities such as lectures and discussions. However, it is the out-of-class activities such as homework assignments that have the greater impact on the students' level of engagement and learning in the course, because they require a more active (and protracted) form of participation from the student than mere lecture attendance. Improving homework assignments can therefore yield a potentially higher return on the efforts invested in instructional improvement. Since the most common form of assignment used in engineering education is problem solving, this article is concerned with the improvement of classroom problems and their educational value.

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Assignments Used In Engineering Education

Historically, engineering was learned in the apprenticeship mode via project work and case studies, which remains the dominant mode of learning in many professional fields such as law, medicine, and business management. Projects and case studies are valuable because they illustrate the domain or scope of a field, exemplify interaction or tradeoff between multiple goals and constraints, demonstrate an expert's modus operandi, and motivate the learner by their reality and context. Because project work can closely mirror real-life engineering work, its validity as a learning vehicle is automatically criterion-referenced.

By contrast, typical modern engineering education, particularly in the United States, relies heavily on problem solving. Problem solving is demonstrated in the classroom and textbooks, is assigned for homework and drill, occupies the lion's share of the students' study time in a course, and determines who passes an engineering course and with what grades. Moreover, engineering textbooks include extensive end-of-chapter problem collections, publishers urge authors to include more problems in their textbooks, and compilations of solved problems (a la Schaum's Outlines) outsell the bestselling textbooks in their field. Indeed, the workload due to homework problem sets influences the students' course selection and scheduling decisions, distinguishes engineering from other educational fields, and is the subject of numerous jokes about engineering students on the university campus (see the "You Must be an Engineer If" sidebar).

Tradtional Engineering Classroom Problems

At the outset, it would be best to define exactly what we mean by a "problem" in the context of an engineering course. A typical engineering classroom problem encountered by undergraduate engineering students tends to be

- narrowly focused, concerned with very few issues (and often only a single one) at a time
- quantitative, requiring symbolic or numerical manipulation
- closed-ended, with a single, well-defined right answer
- presented in a discipline-centered rather than problem-centered manner, usually stripped of any real-world context
- tersely stated (in at most a few sentences), making its proper, unambiguous interpretation difficult without reference to the course material or textbook in which it is anchored through terminology, notation, implicit information, unstated assumptions, etc.

While this is by no means the only kind of problem used for pedagogical purposes, it will be the focus of our attention because it is the most common type.

The classroom problems of the above type, which form the bedrock of modern engineering curriculum, are at best a caricature of, and a low-cost substitute for, the projects and case studies mentioned earlier. This substitution occurs for a number of practical reasons, including the following:

- to gain flexibility in course design, because project work may not parallel the desired content or sequence of course material, while the problems can be selected to match it
- to allow a broader sampling of the curricular content, because the problems can be far more numerous than projects which take up more time
- to eliminate the cost and overhead associated with projects and case studies
- to accommodate the growth in technological knowledge via idealization [1]
- to reduce the time and proficiency demands on students as well as teachers (and to save the instructor from the large effort required for developing case studies, so as to make room for certain other activities having a higher value in the academic reward system).

The Rationale for Problems

Declarations such as "engineering is a problem-solving profession" are not a valid justification for the heavy reliance of engineering education on problems. Unlike project work, classroom problems replicate very few activities actually encountered in the practice of engineering; these include some standardized engineering examinations for professional licensing, graduate admissions, or screening and selection for employment. As these examinations, which do not represent the full range of professional engineering work, themselves mimic university examinations, they cannot be used as a criterion of validity without the risk of circular reasoning. At best, problem solving is required as one of the essential steps in many types of professional engineering work.

The reason the teaching of engineering rests so heavily on solving problems lies in the multiple roles served by the problems, both as learning vehicles and as assessment tools. As a learning vehicle, the problems can motivate students; specify the domain of learning; serve as a context for learning; demonstrate the application of principles; clarify the procedure or logic; exemplify the use of strategies or skill; illustrate elements of professional work; and provide students opportunities for active learning, practice, and exploration. As an assessment tool, the problems allow the measurement of student achievement for purposes of diagnosis, feedback, and certification.

Problems have other uses as well. One important purpose of classroom problems is to teach the general problem-solving strategies and skills [2] that transcend the disciplinary fields and are useful for a diverse range of activities, including professional engineering work. The value of problems has also been recognized as a basis for instructional organization. There exist instructional methodologies such as Problem-Based Learning (PBL) [3], in which the problems motivate and drive the acquisition of knowledge, as opposed to the principles-based approach in which problems illustrate the use of the knowledge after it has already been presented. Finally, examination problems may be the most accurate statement of course objectives, more trustworthy than the officially declared ones, because the students learn best what the examinations test and not what the instructor hopes, plans, or attempts to teach. More generally, the problems solved in a course constitute a definition of the scope, level, objectives, and content of a course [1]. Of course, it would be very desirable to reverse their roles, and have the course objective define the scope of problems rather than the other way round. That desire motivates this article.

You must be an engineer if

- Your life is a steady series of problem sets, punctuated by exams and semester breaks.
- Your last girlfriend or boyfriend dumped you because you spend Friday nights solving problem sets.
- The numbers in your little black book are the physical constants needed to solve problems.
- Your worst nightmare is that you could not turn in the homework problem set on time.
- Everything highlighted with a yellow marker in your textbook is a formula for solving some problem.

Culled from a T-shirt, a poster sold by the student chapter of an engineering society, and a Web site on engineering humor.

Given the numerous roles of problems, improving them appears to be a very worthwhile goal, particularly since it can be accomplished simply through a judicious selection and framing of questions, which is the central theme of this article. In fact, making the problems more effective is one of the least disruptive methods of implementing a change in instruction, because it does not require any institutional changes, authorization, special training, or scheduling and can be carried out single-handedly by the instructor.

Factors Influencing the Effectiveness of Problems

Implicit in the goal of improving the homework assignments and test problems is the admission that not all problems are equally effective. A problem can be unsuitable for a student if it makes unreasonable intellectual, motivational, or time demands on the student, as in the following instances:

- It may not be matched to the type or current level of intellectual development of the learner, e.g., an abstract problem for a concrete thinker in Piaget's terms [4].
- It may not engage the learner's interest, e.g., due to unfamiliarity of context or lack of relevance to their cognitive framework.
- It may be inefficient in its use of learner's time, e.g., due to a large overhead created by busywork with little educational value or extraneous details not germane to the concept being taught or tested.

Such shortcomings of the problems are avoided, or at least quickly discovered, if engineering students are well prepared (i.e., they have reached a sufficient level of maturity, are motivated to learn engineering, and are active participants in learning). What is more likely to escape undetected is the failure of the problems to contribute to the more significant goals of education, such as conceptual development or critical thinking in the students.

The widespread use of problems can sometimes lead us to have a blind faith in the efficacy of problem solving as a means of subject matter learning and conceptual development, which may be misplaced. Much empirical evidence, both anecdotal and systematic [5], suggests that, in practice, the value of problem solving may have been overrated. Solving problems does not necessarily improve comprehension, because many problems can be solved mechanically without comprehension of the corresponding subject matter. This shortcoming appears to arise not from the use of the problems per se, but from the choice of ineffective problems, and further underscores the need for careful problem selection and construction. This will be demonstrated with the help of a number of examples.

All problems presented as illustrative examples in this article are deliberately taken from a single topical area, so as to 1) allow a direct comparison between them; 2) demonstrate the ability to construct problems that address a variety of educational objectives within the same disciplinary boundaries; and 3) emphasize that it is the selection and construction of the problem, and not the topic, that governs the educational objectives addressed by the problem. The chosen topic is the subject of noise figure of cascaded linear two-ports, a small instructional module that typically occupies less than a classroom hour or a couple of pages in the textbook. Typically, the textbook treatment of the subject culminates in the derivation of the "formula" for computing the noise figure of a cascade of two stages in terms of the noise figures of the individual stages and the power gain of the first stage:

$$F_t = F_1 + \frac{F_2 - 1}{G_1}. \qquad (1)$$

This subject is common to, and included in, numerous courses and textbooks on circuits, electronics, microwave engineering, random signals, communication theory, telecommunications engineering, and other fields.

An Example of an Ineffective Problem

As an illustrative example of a problem that might be devised to test the students' learning of the abovementioned topic, consider the following question that is amenable to a mechanical solution:

Question 1. In a two-stage amplifier, the first stage has a noise figure F_1 of 1.8 dB and a gain G_1 of 10 dB, while the second stage has a noise figure F_2 of 4 dB. Find the two-stage amplifier noise figure F_t.

For a test-savvy student focused on finding the answer with minimum effort, solving this problem is essentially an exercise in 1) searching through the relevant textbook or chapter to locate an equation that relates the given variables F_1, F_2, and G_1 to the required variable F_t, and then 2) substituting into it the numerical values of the known variables to calculate the unknown one. If one were to be generous, solving the problem also teaches the students 3) the typical range of values of the pertinent variables, 4) the need to convert from dB to dimensionless numeric units before using the equation, and 5) that the power gain of the second stage is irrelevant to the overall noise figure. None of these skills was likely the central objective that the instructor composing the question had in mind. Students have long described this type of problem as "plug-and-chug," "turn the crank," or "Mickey Mouse" variety. Sometimes, the problem can be solved by other subterfuges, such as matching dimensions of physical variables, which still do not require any topic-specific knowledge or skill.

The shortcomings of the problem are numerous.

- The question as stated can be solved without having any knowledge or understanding of the utility and implications of the two-stage noise figure formula, how its use is constrained by the conditions employed in its derivation, or anything else about the derivation, which was the subject matter presented in the classroom or textbook and upon which the question is based.
- The question also does not require any familiarity with even the more rudimentary constituent ideas or terms upon which the question is based, such as what is the noise figure.
- The question takes a lot for granted; for example, it assumes that the given power gains are available power gains and that the given noise figures for the stages are valid at the source impedances actually encountered by each stage in the cascade connection. Such tacit adoption of assumption has the great pedagogical drawback that it teaches the students to be casual in the use of a ready-made formula and indifferent towards ascertaining the scope of validity,

or domain of applicability, of data and equations.

- The question is poorly constructed even as a vehicle for testing the recall of the correct formula, because a student using the incorrect formula

$$F_t = (F_2 - 1) + (F_1/G_1)$$

would still arrive at the correct answer.

Despite all of its shortcomings, a question of this type can be found in literally dozens of textbooks (and, dare I say, professors' assignments and quizzes). In particular, the question certainly does not prompt the students to engage in any creative thinking.

Relationship to Instructional Objectives

The effectiveness of a problem can only be assessed with reference to the purpose that the problem is meant to serve, and that purpose itself must be in support of the objectives of learning. While it might appear that the objectives of learning can only be discussed in the context of a specific subject matter, educational psychologists who have studied the nature and construction of educational objectives in depth have discovered a set of underlying basic intellectual abilities useful for framing educational objectives that transcend the subject matter details and that lend themselves to a generic description that is surprisingly broadly applicable across all academic disciplines.

One possible way of understanding and organizing educational objectives is to employ Bloom's taxonomy of educational objectives, which is considered to be one of the most influential ideas in education in the past half-century and is widely accepted and taught worldwide. Benjamin Bloom of the University of Chicago headed a group of educational psychologists in the mid 20th century who adopted a behavioral definition of learning and developed a classification of intellectual behaviors displayed by learners, now commonly called Bloom's taxonomy. They subdivided human responses to instruction in three domains: cognitive, affective, and psycho-motor, dealing respectively with intellectual [6], emotional [7], and mechanical behaviors [8] demonstrated by learners. Within the cognitive domain, they further identified six major categories of abilities, which could be organized in a hierarchical order, starting from the simplest and concrete ones and progressively including more complex and abstract abilities as shown in Table 1. For each ability, the table also lists the manner (paraphrased from Bloom's original description) in which a learner demonstrates that ability.

The taxonomy of educational objectives is far more significant and useful than a mere inventory of objectives, because the identified abilities and their arrangement are commonly believed to have (or approach) the following desirable characteristics:

- Universality: The set of abilities transcends the subject matter content, applying across virtually all academic disciplines, irrespective of student level (elementary school to university) and teaching philosophies.
- Comprehensiveness: The categories in the taxonomy, although small in number, include all cognitive abilities, so that all educational objectives, although they can be expressed in an almost unlimited number of ways, are represented within the taxonomy.
- Distinctness: The various abilities included in the taxonomy are separately and individually identifiable, and are therefore distinct and distinguishable from each other.
- Cumulative Hierarchy: The cognitive abilities are organized in the order of increasing complexity, such that the abilities in the lower-level categories (appearing higher up in the table!) constitute the antecedents for the abilities at the higher levels. As a result, acquiring proficiency with the lower-level skills is essential to attaining a higher-level skill.

Revised Bloom's Taxonomy

With the benefit of the experience of using the taxonomy for nearly half a century, and the ensuing research and discussions during the intervening years, another group of workers (which included some of the original team members) announced a somewhat revised version of Bloom's taxonomy [9], [10] in 2001. This taxonomy is more teacher-friendly because it organizes the objectives in a manner that parallels the way instructors state their educational goals: by stating both the knowledge to which it relates and what the learner is expected to be able to do with that knowledge. The statement of an objective therefore has two separate dimensions: a behavior or process to be performed by the learner, and the content or knowledge on which it is to be performed. The revised taxonomy maintains the distinction between the two dimensions and classifies each of them separately. The process dimension is classified into six major categories, ranging from remembering to creating, which are still further subdivided into 19 subcategories, as listed in the left half of Table 2. The knowledge dimension is similarly classified into four major categories, which are then further subdivided into 11 subcategories as shown in the right half of Table 2.

TABLE 1. Bloom's original (1956) taxonomy of educational objectives in the cognitive domain.

Cognitive Ability	Behavioral Manifestation
1) Knowledge	Recalling and reproducing information
2) Comprehension	Relating information to prior knowledge and organizing it
3) Application	Using information in a specific situation correctly
4) Analysis	Identifying constituent elements or components of complex information
5) Synthesis	Combining or relating distinct components or elements of information in a single context
6) Evaluation	Assessing and judging information to arrive at a conclusion

A pair composed of a process skill from the left half of the table along with a knowledge category from the right half together constitutes an ability that a learner might acquire; it is stated in behavioral terms as the manner in which the learner can display having acquired that ability. If that ability is the objective of learning, then the pair (a process skill plus a knowledge type) is also a statement of a task that the learner must perform so as to demonstrate having achieved that learning objective. As a result, it simultaneously specifies what a learner should be asked to do so as to determine whether the intended lesson has been learned, which is the function of a classroom problem. Table 2 is thus a prompting device that is suggestive of what problems to construct for use in the classroom, homework assignments, and tests; the remaining question of how to construct them is addressed in the remainder of this article.

While other revisions of Bloom's taxonomy have also been proposed (e.g., [11]) and employ different terminology, when those terms are interpreted in the context of engineering, there is a very large degree of agreement between them. The classification of the process dimension of a cognitive ability, shown in Table 2, will therefore be employed in the remainder of this article to guide our discussion of the selection and construction of classroom questions. The action verbs used as names for the six categories of the process dimension, along with their subcategories, are useful for organizing the problems according to the educational objectives; they will be defined in detail and illustrated by examples in the next section.

The first three categories of knowledge types are mostly self-explanatory and are further described by their subdivisions. The last category, called metacognitive knowledge, refers to 1) a knowledge of the learning, thinking, and problem-solving strategies that are broadly useful for a variety of tasks; 2) knowledge about the tasks as to the usability and appropriateness of particular procedural or heuristic strategies for them; and 3) self-awareness or knowledge of the learner's own capabilities, limitations, and tendencies when working on cognitive tasks. Metacognitive knowledge is important because it enlarges the learner's repertoire of problem-solving tools, permits the transfer of learning from one situation to another, and facilitates adapting to the type of task at hand. It is included in the taxonomy not because an instructor will assess this knowledge by tests, but because the instructor can help increase it through explicit attention to it, e.g., by demonstrating problem-solving strategies, comparing alternative strategies, and discussing how and why a strategy is selected for a task at hand. There are many other proposed classifications of knowledge types based on different perspectives, some of them particularly relevant to engineering disciplines [2], which could also be employed here.

TABLE 2. Revised (2001) Bloom's taxonomy of educational objectives in the cognitive domain.

Process Dimension		Knowledge Dimension	
1) Remembering Retrieving relevant knowledge from long term memory	1.1 Recognizing 1.2 Recalling	**1) Factual** Needed for acquaintance with a discipline, or to solve problems in it	1.1 Terminology 1.2 Specific Details and Elements
2) Understanding Determining meaning of instructional messages, including oral, written, and graphic communication	2.1 Interpreting 2.2 Exemplifying 2.3 Classifying 2.4 Summarizing 2.5 Inferring 2.6 Comparing 2.7 Explaining	**2) Conceptual** Interrelationships among elements within a larger structure that enable them to function cohesively	2.1 Classifications and Categories 2.2 Principles and Generalizations 2.3 Theories, Models, and Structures
3) Applying Carrying out or using a procedure in a given situation	3.1 Executing 3.2 Implementing	**3) Procedural** Methods of inquiry or methodological skills, and criteria for their use	3.1 Subject-Specific Skills & Algorithms 3.2 Subject-Specific Techniques and Methods 3.3 Validity or Applicability Criteria for Procedures
4) Analyzing Subdividing information into constituent parts, and detecting their relationship to one another and to the overall structure or purpose	4.1 Differentiating 4.2 Organizing 4.3 Attributing	**4) Metacognitive** Awareness of general, and one's own, cognition	4.1 Strategic Knowledge 4.2 Cognitive Tasks 4.3 Self Knowledge
5) Evaluating Making criteria-based judgments	5.1 Checking 5.2 Critiquing		
6) Creating Assembling elements together to form novel or original structure	6.1 Generating 6.2 Planning 6.3 Producing		

Putting the Taxonomy to Use

Often the goals of education are stated at a global level, diversely described as mastery-level proficiency, critical thinking, and creativity, which are complex and must be operationalized. For example, critical thinking has been variously defined as an amalgamation of a number of abilities: exploring a problem, question, or situation; discerning implicit assumptions; examining beliefs and hypotheses; evaluating evidence; assessing conclusions; integrating all available information; and others. The utility of Bloom's taxonomy lies in providing the educators from different disciplines a common vocabulary for discussing the educational goals, analyzing the meaning of globally stated educational goals such as "creative thinking," laying out a road map of the steps to reach those goals, making available a checklist for ensuring that essential skills do not get ignored in the process of reaching those goals, and exposing that shortcoming when they are overlooked. Conversely, given the curriculum, instructional materials, and assessment tools, the taxonomy can be used to evaluate what goals and cognitive abilities are, or are not, being served.

While the taxonomy is useful for a wide variety of purposes [9], only those of its applications that are directly relevant to the construction of classroom problems are of concern here. For a classroom instructor, the taxonomy is a checklist of abilities to consider in instruction and a prompting device for constructing learning exercises and problems for assessment. The behaviors at the higher levels of Bloom's taxonomy (analyzing, evaluating, and creating) can be recognized as the basic elements of the larger educational goals such as critical thinking. To assist a learner in becoming a critical thinker, the instructors must 1) be aware of the hierarchy of skill through which learners will need to progress to attain the higher goals; 2) adapt their teaching methods, materials, and approach to promote these skills; 3) include activities aimed at the higher-level abilities—and since the abilities are hierarchical, also the requisite abilities at other levels—in their instructional design; 4) provide learners with opportunities to practice and exhibit the behaviors corresponding to the abilities at various levels; and 5) assess whether the desired goals are accomplished. The taxonomy is useful for each of these tasks.

If, as in engineering education, problem solving is the principal learning vehicle, then the problems are the means both for assessing a cognitive ability and for promoting its growth in the learner. A problem can stimulate the learner to engage in an activity that develops a cognitive ability by challenging, exemplifying, and exercising that ability. To engage the learners in critical thinking and the higher-level abilities from Bloom's taxonomy, it follows that the instructor will need problems aimed at many levels of abilities. The development of such problems is discussed in the remainder of this article, which demonstrates how to construct questions to address each of the six major process categories in the revised Bloom's taxonomy, along with examples of each.

Questions Requiring Remembering

A question that asks the learner to either recognize some information, or recall it from memory, in essentially the same form in which it was previously presented to him, prompts him to engage in the process of remembering. While it may not appear to be very meaningful, remembering is an essential antecedent to the use of that information in higher-level cognitive abilities. On any topic, questions that can be answered entirely by a memorized answer are easy to pose. Consider the following example, which requires a simple recall of a result.

> **Question 2. A preamplifier is introduced ahead of another (the "second-stage") amplifier to create a two-stage linear amplifier. Express the overall noise figure of the two-stage amplifier in terms of the noise figure and the available power gain of the individual stages**.

In this problem, nothing more is required than reproducing the algebraic relationship expressing the desired variable in terms of some or all of the given ones. Although very similar to Question 1 (cited earlier as an example of a poorly framed question), this problem is stated in technical terms rather than algebraic symbols, and therefore requires the student to recognize the terms instead of working with a symbol that permits dispensing with the term. In an open-book examination, the student will need only to recognize, rather than recall, the answer.

The ability to recognize can also be tested by questions in which the student need only select (rather than produce) the correct answer, such as multiple-choice and true-false questions (sometimes called objective tests, although the only thing objective about them is their scoring, which can be mechanized). Such questions are particularly suitable for testing the attainment of some educational objectives at the lower levels of the hierarchy, one of which is recognition. Thus, consider the following question:

> **Question 3. If a preamplifier with noise figure F_1 and available power gain G_1 precedes a second stage of amplifier with an operative noise figure F_2 and available power gain G_2, the noise figure F_t of the overall two-stage linear amplifier is given by**
>
> a) $\mathbf{F_t = (F_1/G_1) + (F_2/G_2)}$
> b) $\mathbf{F_t = (F_1 + F_2)/(G_1 G_2)}$
> c) $\mathbf{F_t = 1 + [(F_1 - 1)/G_1] + [(F_2 - 1)/G_2]}$
> d) $\mathbf{F_t = F_2 + [(F_1 - 1)/G_1]}$
> e) $\mathbf{F_t = F_1 + [(F_2 - 1)/G_1]}$.

Notice that in each of the offered answers, the gain always divides the noise figure and never multiplies it; such internal consistency among proposed answers makes the responses more plausible and prevents a discrimination between them based on partial knowledge or arguments.

While such objective questions are commonplace in many disciplines, may be necessary for testing large numbers of students, and are employed in many standardized tests like the Graduate Record Examination, they are often shunned as being too shallow and trite for engineering subjects and classroom use. Many of the claimed shortcomings of such questions are, however, not inherent in this type of question, but result from a lack of attention and time required for constructing a good question or for providing plausible but incorrect answers against which to discriminate the correct answer.

Questions Requiring Understanding

Understanding occurs when a learner connects a newly acquired knowledge to his prior knowledge, which allows him to construct a meaning for that knowledge. It is evidenced by the learner's ability to transform that knowledge in some way, such as by paraphrasing, interpreting, or explaining, so that it is in a different form than the one in which it was originally presented to him. This information transformation ability can be demonstrated in any one of a number of ways listed in Table 2 in approximately the order of increasing difficulty. The importance of understanding stems from the fact that it is essential to the transfer of knowledge from one context to another.

A straightforward way of constructing a question that explores and challenges a learner's comprehension of a topic is to directly ask for a learner's interpretation or understanding of it, as in the following problem:

Question 4. Explain in your words why the addition of a low-noise preamplifier stage before a linear amplifier lowers the overall noise figure of the composite amplifier?

Since the question leaves the level and scope of the explanation up to the student, the answers can vary widely in their depth and issues addressed, and may be more useful for diagnosis than for a precise assessment of the learner's understanding. Such a general question allows the degree of understanding of the learner to be inferred from the preciseness, richness, and generality of the explanation provided by the learner. On the other hand, a more specific question that draws the learner's attention to the issue of interest allows exploration of the nuances of the learner's understanding and minimizes the variability in answers arising solely due to the differences among learners with verbose and tacit tendencies. Here is an example.

Question 5. Explain the manner in which the magnitude of the gain (or the loss) of the first stage determines the degree of influence that the second stage noise figure has on the overall noise figure of a linear two-stage amplifier.

Understanding can also be demonstrated by explaining the reasons and rationales underpinning, or implicit in, the knowledge at hand. Thus, Question 5 could also ask for a related explanation for the load-independence of the noise figure or the assumptions concerning the source impedance presented to the second stage that are implicit in using (1).

Questions requiring a display of understanding need not necessarily be descriptive; a quantitative question can ask the learner to carry out a quantitative rather than verbal transformation of the knowledge. As an example, the following question on understanding explores the same domain of knowledge as Question 4 above.

Question 6. A two-stage linear amplifier is created by introducing a preamplifier stage ahead of a second-stage amplifier. In order to make sure that this action results in lowering the overall noise figure of the two-stage amplifier below that of the second stage alone, how low must the noise figure of the preamplifier be, i.e., what is the threshold value (upper limit) of the noise figure of the preamplifier stage?

Detailed assessment of an individual's level of comprehension of a subject by necessity requires testing that individual's ability to make fine discriminations, for which an objective question might be particularly well suited, because it can purposely draw the learner's attention towards potential areas of confusion. Here is an example.

Question 7. Why does the noise figure of a linear two-stage amplifier depend (other parameters remaining unchanged) on the available power gain of only the first stage, but not of the second-stage amplifier?

a) The noise figure of a two-port is well known to be independent of the termination at its output port, and the second-stage amplifier is effectively just a termination at the output port of the first-stage amplifier.
b) The presence of the preamplifier prevents the source impedance of the second-stage amplifier from changing, thereby making the second-stage gain and noise figure constant, so that the second-stage gain is no longer an influencing variable.
c) While the first-stage gain amplifies the signal when it is weak and susceptible to noise, the amplification by the second-stage gain occurs at a point where the signal has already been strengthened by the first stage, so it does not influence the overall signal-to-noise ratio or noise figure.
d) While the first-stage gain does not amplify the noise power added by the second stage, the second-stage gain amplifies both the signal and the total noise (including that arriving at its input, plus that generated within but referred to its input port).
e) Cascading two amplifiers narrows the effective bandwidth of the overall amplifier, which in turn governs the noise power within the passband; it is this bandwidth rather than the gain of the second stage that determines the signal-to-noise ratio and the noise figure.

In this problem, each of the incorrect answers starts out with a reasonable preamble in its first clause to capture the interest of the learner having a smattering of some related bits of information. The level of difficulty of this question can be varied by changing the plausibility of offered incorrect choices of answers.

Questions Requiring Applying

A question invokes the cognitive ability to apply when it requires the learner to carry out a procedure or method. Carrying out the application in a familiar setting is called "executing," while in an unfamiliar setting it is called "implementing." Although a routine application of a procedure does not by itself involve critical thinking, the skill of "applying" is nevertheless important, because critical thinking may include many such routine applications of procedures, often carried out without overt thought.

Problems on executing are commonplace in engineering, because the use of a routine procedure, a standard result, or even the substitution of numerical values in a formula constitutes an "application" of the result, as in the following.

> **Question 8. In a two-stage linear amplifier, the first stage has a noise figure of 2 dB and available power gain of 10 dB specified at the actual source impedance, while for the second stage those parameters are 4 dB and 20 dB, respectively, at a source impedance equal to the output impedance of the first stage. Find the noise figure and gain of the two-stage amplifier**.

Answering this question requires an application of the result in (1) to calculate the desired quantity, which can be considered as applying a procedure. Because such questions on applying are easily constructed, they are some of the most abundant in engineering textbooks at all levels, from technology programs to the graduate level. Question 8 is similar to Question 1, except that it is stated in physical rather than symbolic terms, thereby ensuring that the application process is not decoupled from the subject-specific knowledge domain to which it relates. However, many of the reservations voiced concerning Question 1 are still applicable, because the calculation in Question 8 can be carried out with relatively little engagement with the subject matter content.

By contrast, "implementing" is a more demanding ability, because it requires a transfer of knowledge from the familiar to an unfamiliar setting. As a result, the learner needs both the knowledge and understanding of the background to the question (the two lower-level skills in the hierarchy), which are then used in carrying out the required procedure. The following problem exemplifies the process of implementing.

> **Question 9. A given amplifier stage is preceded by a preamplifier and followed by a postamplifier, thus creating a three-stage linear amplifier. What is the overall noise figure of this three-stage amplifier, expressed in terms of the noise figures and available power gains of the individual stages?**

This problem relates to a three-stage amplifier, which is a different setting than the familiar one to which the two-cascaded-stages noise figure formula can be routinely applied. In addition to implementing a subject-specific method, this question also requires the use of some general problem-solving strategies, including partitioning the problem and applying a procedure iteratively, which are commonly employed, for example in the method of induction. If these strategies are not present in the repertoire of tools possessed by the learner, the question would require higher cognitive abilities that would be considered critical thinking. The process of implementing can become more demanding in other ways as well, e.g., when the learner must select a procedure from among multiple possibilities or when the applicability of the procedure must be tested before use.

Questions Requiring Analyzing

Analysis involves the breaking up of a complex situation or information into its elementary constituents, which might then be addressed by lower-level cognitive skills such as understanding. The tasks of subdividing into parts, relating them to each other or to the whole, and characterizing each part constitute the cognitive processes involved in analyzing. Although analysis might appear to be simply a technique for understanding, or a technique for creating (as is well known to engineers who, for example, optimize designs by iterative analysis), it is indeed a separate cognitive process– distinct from understanding and creating–that can be taught, learned, and tested.

The cognitive abilities of analyzing can be prompted through questions that require separating, subdividing, disassembling, or differentiating the given information, which are the hallmarks of the analysis process. Such a subdivision can then be followed by classifying, categorizing, or organizing those parts in a diagram, hierarchy, or schema that shows the relationships between them, or by discriminating, comparing, or contrasting the individual parts on the basis of some feature or characteristic. An example is exhibited in the following question.

> **Question 10. A cascade of two linear two-port networks is driven at its input port by a one-port linear source network. At the relevant source impedance, the first two-port has an available power gain of G_1 and a noise figure of F_1; for the second two-port, the corresponding quantities are G_2 and F_2, respectively. The source is known to have an available signal power S_s and an effective noise temperature T_s. Determine the ratio of available signal-to-noise power at each of the three ports: (S_s/N_s), (S_i/N_i), and (S_o/N_o), where "s" denotes the source network port, "i" denotes the intermediate port between the two stages, and "o" denotes the output port of the entire network. Suggestion: Draw a signal flow diagram showing the relationship between the three**

available signal powers S_s, S_i, and S_o at the three successive ports, and another diagram showing the relationship between the three available noise powers: N_s, N_i, and N_o at the same three ports; then use these two diagrams to find the ratios.

This question entails distinguishing between and separating the transmission of signal and noise powers through the network, and furthermore, subdividing the noise powers at each stage into two parts: that attributed to the noise added by the stage and that arriving at its input. The problem thus calls for analyzing. In addition, it also requires other skills from the lower levels of the hierarchy of cognitive abilities, such as the recalling of information (e.g., the definition of noise temperature), understanding of procedural applicability (e.g., the additivity of noise powers if uncorrelated), and applying a knowledge-specific procedure (e.g., determining the noise power added by a stage from a knowledge of the noise figure of that stage).

Questions Requiring Evaluating

A learner engages in the process of evaluating when a question calls for deduction and judgment, applied to some information that is either supplied to or generated by the learner, on the basis of some explicit criteria. If the judgment calls for verifying the internal consistency of the information, the evaluation is classified as "checking." By contrast, when the basis of judgment is a criterion that is external to the information being judged (i.e., must be separately specified in addition to the information being judged), the process is termed "critiquing." Clearly, critiquing could also be viewed as checking for consistency between the external criterion and the information being judged.

An evaluative ability can be demonstrated in a variety of ways, e.g., by presenting the learner with assertions, options, or inputs in some situation and then asking him to compare, criticize, defend, consider, conclude, assess, predict, select, or recommend. The following problem illustrates the use of evaluating ability.

Question 11. For the measurement of its noise figure, a low-noise amplifying device is mounted in a passive fixture that is lossy, and its noise figure is then calculated as the ratio of 1) the measured noise figure of the fixtured device and 2) the attenuation introduced by that part of the fixture preceding the device. Assess this method with respect to the uncertainty in the estimated device noise figure by considering a) the assumptions implicit in it; b) its usability when the device gain is low; c) the determination of the attenuation of the relevant part of the fixture; and d) the fixed measurement uncertainty of $\pm\Delta F$ in the measured noise figure of the fixtured device due to the instrumentation limitations. In particular, would it be desirable to have a high fixture attenuation so as to determine the device noise figure with a low uncertainty?

This problem specifies a criterion of effectiveness (low measurement uncertainty) for judging the method in question. It also calls for adopting reasonable postulates about the situation (e.g., concerning the fixture temperature), discovering hidden assumptions implicit in the method (e.g., impedance matched operation), accounting for multiple factors to assess the usefulness of the method (e.g., the need to make a loss measurement); considering special cases and particularly stringent conditions (e.g., low-gain devices); and making evaluative judgments based on the various elements of the evidence collected. These activities are typical of the tasks and behavioral responses involved in the process of evaluating. An instructor could also phrase a question to explicitly ask the learners to examine a particular aspect of the problem (such as the need to introduce an auxiliary amplifier in the measurement setup) or consequences of the situation (e.g., the effect of fixture loss on enhancing the noise contribution from the measuring receiver) to overcome the variability in answers due to learner fluency.

Questions on evaluation would almost invariably be perceived as being difficult, for two reasons. First, a situation requiring an evaluative judgment will typically not be specified completely, uniquely, or precisely; instead, it will often expect the learner to use assumed, proposed, estimated, experimental, or guessed information on a trial basis, subject to subsequent testing, checking, or examination. Second, a question asking for evaluation, even if it has a definite answer, will likely not offer the security of a well-defined step-by-step procedure to arrive at an absolute and unequivocal determination of the answer. A consideration of the many alternatives, options, or possibilities and the ramifications of the trial information in an incompletely specified situation may require knowledge of related subjects beyond the topic at hand. As a result, learners with prior related exposure would have an advantage over others in answering such questions. This is apparent in the above problem, which does not numerically specify the fixture loss, device gain, or instrumentation uncertainty. Thus, prior experiences, e.g., with device fixtures and noise figure measurements (topics that lie outside the scope of the narrow instructional module from which the question is taken), would embolden the learner in making and assessing the reasonableness of assumptions, approximations, and estimates.

A particularly efficient method of constructing questions on evaluation is to base them on items in the professional literature, including articles in engineering journals and trade magazines, patents, application notes, product data sheets and announcements, industry reports, and other similar documents. The following is such an example.

Question 12. Consider the results reported in the following article:

S.M. Bozic, "Noise figure of cascaded networks and the role of available power gain," *Int. J. Elect.*, vol. 47, no. 2, pp. 201–202, Aug. 1979.

Determine the relevance and impact of the reported results for a mismatched cascade of stages

having the specifications of the two-stage wireless system amplifier discussed in class.

Since evaluating such literature is a normal part of professional activities for an engineer, such problems have high educational validity. The amount of work required of the learner can be minimized by selecting shorter articles (as in the example above), employing only the excerpts from the original materials, and by limiting the scope of the critique to a specific issue or aspect of the subject matter. For the instructor, the task of constructing problems is largely replaced by that of locating suitable items of professional literature, which may be no less time-consuming. Since the articles chosen for critique must be accessible to a reader at the level of the learners and include something to evaluate, there may be better prospects of finding suitable material in trade magazines that are more likely to publish questionable or imprecise statements, and in older journals (such as in the example above), particularly if the hindsight resulting from more recent developments opens up new vistas.

Questions Requiring Creating

The process of creating involves integrating multiple elements of information, which are either known or can be arrived at via the lower-level cognitive processes, to assemble a structure that is novel to the learner. Although the creative process is described very differently in different disciplines, a widely applicable model is to subdivide it into the cognitive steps of generating (the alternatives, solutions, hypotheses), planning (the subgoals, phases, stages), and producing (the synthesis, design, result), each of which could serve as the basis of a question.

In engineering disciplines, design problems are common, and typical examples of questions that call for creating. However, the design of an engineering object is not the only way to demonstrate the ability of creating; when in response to a question the learners model, construct, hypothesize, formulate, combine, or incorporate, they employ some of the elements of the creating process. This is useful because an entire design task may well be too large and complex, involving a multitude of skills, and requiring more time than is available for practicing problem solving within a single instructional module or unit.

The following is an example that explores the cognitive process of creating, through a question within the confines of the narrow scope of the topic at hand.

Question 13. A C-band satellite receiver consists of an outdoor receiving antenna, followed by a 10-m long cable with an attenuation of 0.3 dB/m that is used to bring the received signal indoor. Thereafter, the signal is filtered by a bandpass filter having a loss of 2 dB, and further amplified by a low-noise and a second-stage amplifier, each with a gain of 15 dB, but with noise figures of 1 and 2 dB, respectively, before being applied to the remainder of the receiver. Propose some methods for improving the noise performance of the receiver front-end, estimate the improvement achievable by each, list the tradeoffs for each method and the basis on which to select one of those methods.

The question asks the learner not only to demonstrate the creating ability as the first step by generating alternative receiver front-end architectures, but also to construct reasonable hypotheses and models for elements of the problem (e.g., treating the cable as a passive linear two-port in equilibrium), which also calls for the creative ability. Answering the question further necessitates the use of some of the lower-level skills in the hierarchy of cognitive abilities, including applying procedures (e.g., combining the noise figures of the cable and amplifiers), analyzing (e.g., developing a relationship between the attenuation and noise figure of the cable), and evaluating the proposed architectures based on multiple criteria of success (such as cost if antenna size is to be increased, and risk of saturation if the amplifiers are to precede the filter). The learner is also required to acquire related information (e.g., representative values of antenna noise temperatures in the satellite band) to determine whether the proposed solutions result in a significant improvement, and to relate the knowledge drawn from a number of sources (e.g., typical noise specifications for available low-noise amplifiers that are suitable for outdoor use) in arriving at the answer.

Selecting the Problems

Many skills are essential for engineering work, and ideally, they would all be represented in the learning repertoire as much as possible. In practice, this may not be feasible, given the constraints of time, personal preferences, and the fact that some objectives may not be easily amenable to learning and assessment via problems. In a course that relies heavily on problem solving, learning is dominated by the abilities that the problems call upon the learner to exercise. Therefore, the selection of problems would likely have to be based on some overarching or global considerations, such as the following:

1) As we have seen, the choice and framing of problems depends on the educational objectives to be achieved. If the goal is to teach critical thinking, then the education program must include both the learning opportunities and the assessment tools for creative thinking. Educational programs that do not challenge the learner with questions aimed at higher-order cognitive abilities risk producing graduates with deficiencies in the areas of critical thinking.
2) A strict cumulative hierarchy of abilities in the taxonomy would imply that all lower-level skills must be mastered before higher-level abilities can be developed. This may not be entirely necessary, and each ability may not require a separate instructional effort devoted exclusively to it. Since questions on higher-level abilities also make demands on lower-level skills, it might be possible to develop abilities at several levels concurrently [12]. This requires a judicious selection of problems to

ensure that the intellectual jump required does not become so large as to frustrate the learners.

3) Problem solving is only a means, not an end. Ultimately, it is the learner's ability to use the learning that is the goal of the learning process. To be truly useful, learning has to be transferable to novel situations. One way of encouraging learners to attempt a transfer of learning from one domain of knowledge to another is through questions that actually require them to do so. Understandably, such questions will require the knowledge and the ability to apply that knowledge from multiple domains, as illustrated by the following example.

Question 14. In a satellite communication system, the receiving antenna has a very low loss and a noise temperature of 150K. Due to a rainstorm, the radio signals traveling from the satellite to the receiver undergo an additional signal absorption of 8 dB over the path length. If the temperature of the rain water is 290 K, calculate the factor by which the signal-to-noise ratio of the system is degraded at the antenna terminals.

This question requires modeling the communication channel as a linear two-port based on the linearity of the channel. That, in turn, allows the channel and the receiving antenna to be viewed as being connected in a cascade, reducing the "novel" situation to the familiar one of a cascade of linear two-ports. Having made that connection, much other knowledge can be transitioned from the domain of linear two-port networks to the domain of electromagnetic wave propagation in a wireless channel, such as assigning a noise figure to the lossy channel and deducing it from the attenuation and physical temperature of the channel, as for any passive linear two-port in equilibrium. The transfer of knowledge is made possible by the abilities of understanding and model construction. The problem also illustrates the benefits of presenting the knowledge to be learned in a more general context (for example, linear two-ports rather than amplifiers) to encourage its broader understanding and transferability.

Significance of Prior Experiences

Although illustrative problems have been provided for each of the six major categories of cognitive abilities contained in the revised Bloom's taxonomy, a problem cannot be inherently and permanently tied to a given ability. For instance, if it is identical to one that has already been solved in the classroom, then it might test only the ability to recall, irrespective of the higher-level ability for which it was intended. Conversely, if the result in (1) and its derivation have not been previously presented to the learner, then the problem in Question 1 would be considered very challenging rather than trivial. The cognitive ability addressed by a problem thus depends on the students' prior experiences. This explains the popularity of solved examples, problem-solving sessions, copies of old examinations, test preparation guides, and test coaching among students: each of them minimizes the novelty of the setting presented by a new problem, and by anticipating various problem types, replaces higher-level cognitive tasks such as analyzing by lower-level tasks such as recalling based on prior exposure.

Similarly, based on their prior experiences, students may solve a given problem in more than one way, each of which displays different abilities, and so the problem may be viewed as representative of different abilities within Bloom's taxonomy. For the same reason, different instructors may assign the same problem to different categories of the taxonomy. Therefore, the educational objective served by a problem cannot be prespecified without consideration of what the classroom activities or other prior experiences of the learners have been.

One unfortunate consequence of the prior exposure effect is the constant need for new problems. If the solutions to all problems assigned in a course in previous years are distributed or available, and the students are to be evaluated based on their problem-solving ability, then the instructor would feel the necessity of developing new problems every semester. The difficulty of coming up with new and meaningful problems, aimed at the higher levels of achievement in Bloom's taxonomy, should not be underestimated.

Developing the Problems

Developing and framing of new problems required to attain higher-level objectives is admittedly not an easy task. The paucity of problems at the higher levels of cognitive abilities, for example in the advanced textbooks, is indicative of the demanding and time-consuming nature of the task of problem construction, as well as the drawbacks being faced by the learners who might have benefited from more and better learning exercises in developing their cognitive abilities.

Since the instructors may often have to construct the problems themselves, the following are some recommendations for making the task bearable. Awareness of Bloom's taxonomy helps make the task of problem construction easier, because the description of the cognitive ability for which the problem is to be constructed, contained in Table 2, itself prompts the questions. Because it requires a high degree of expertise in the subject matter, constructing problems that explore various levels of cognitive abilities is a good training device for advanced students (and teachers!) if they can be recruited. Many instructors already spend much more time than their institutions assign for teaching, and developing problems that they find satisfactory may have to be a part of such bootlegged work. More professionals might be encouraged to engage in the intellectual activity of constructing and solving new and interesting problems if this was recognized as a valid form of scholarship. Professional societies might create, through their publications or other activities, a mechanism for sharing among educators problems in their discipline that are suitable for classroom use. Journals allegedly dedicated to engineering education might provide an outlet for such scholarship by taking a lead in this regard from those in the mathematics and science disciplines.

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Education News

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■ Luziano Boglione

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Educator's Corner *(continued from page 104)*

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