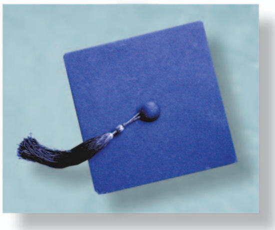

Educator's Corner

Teaching to Facilitate the Transfer of Learning

■ **Madhu S. Gupta**

An amusing anecdote that is old (having appeared in *Esquire* and *Reader's Digest* over half a century ago) concerns a man who experienced severe motion sickness during train travel whenever he would ride backwards, i.e., sat facing the rear of the train; so he learned to exchange such a seat by requesting the passenger sitting opposite to him. When he got off the train very sick and nauseated one day, his friend receiving him at the train station asked what was wrong. He replied that he had been riding the train backwards. "Why didn't you ask the person sitting across from you to change seats with you?" asked his friend. "How could I," said the traveler, "There wasn't anybody in that seat."

The source of amusement in this anecdote, and in many other similar tales, lies in some incident resulting from the inability of a person who has learned to solve a problem in one situation to apply that learning in a slightly different situation. Such a failure arises from the individual's learned behavior being too rigidly tied to the specifics of the situation in which the behavior was originally learned and not being invoked in the absence of the cues that would be generated by those specifics, even though the learned behavior is more generally useful or broadly applicable. In engineer's vernacular, such a failure might be described as an inability to apply or generalize. Cognitive psychologists call this a failure in carrying out a transfer of learning.

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Digital Object Identifier 10.1109/MMM.2009.935201

The success of any classroom-based instructional process, material, or program must ultimately be measured by its success in enabling the learner to utilize the classroom learning in situations outside the classroom. In fact, the very purpose of education is to prepare a learner to apply what has been learned to a newly encountered situation on a subsequent occasion, thus displaying skilled performance as distinct from rote learning. Therefore, the transfer of learning is fundamental to all education, and much of the educational enterprise derives its justification from its ability to facilitate a subsequent transfer of learning. Indeed, the transfer of learning is so pervasive that educators tend to take it for granted. Thus, many textbooks on probability theory and random variables for engineers are replete with problems on coin tossing, shuffling of card decks, and drawing colored balls from urns, not because the students need to be trained as accomplished gamblers or will likely ever have an opportunity to draw balls out of an urn. The expectation is that the students will apply the principles thus learned to the real-world problems of random failures of components, interference due to random noise, availability of systems with fluctuating demands for service, product variability in a production line, and other such situations.

Transfer and How It Is Manifested

Transfer of learning is defined as applying or adapting previous learning to a novel situation. Thus, when a student solves a problem based on, or draws parallels

1527-3342/10/$26.00©2010 IEEE

with, a different problem whose solution he has previously learned, the transfer of learning is directly evident. Similarly, transfer is operative when he is able to solve a problem in a context or setting that is different from the one in which he initially learned the method of solution. But the transfer of learning can also be manifested in less obvious ways, for example when a student's prior learning of some subject makes it easier for him to learn a new subject, as compared with someone who has not previously learned the first subject, due to the commonality of some underlying skills. A negative transfer is also possible, where prior learning interferes with the performance on a subsequent target task. Examples of such forms of transfer that the reader may have observed, or experienced first hand, are given in Table 1.

The transfer of learning is fundamental to all education.

At first sight, *transfer* as defined above might appear to be synonymous with *learning*, but there is a subtle distinction. Learning is a change in the long-term memory of the learner that results in a change in his responses to subsequent stimuli. Transfer is the change, due to the learning resulting from an earlier set of stimuli, in the responses to subsequent stimuli that are novel or different from the original ones. Some degree of novelty is thus an essential requirement in the definition of transfer.

Because we do not yet understand the human cognitive processes sufficiently well to be able to predict, let alone cause, the occurrence of transfer with certainty (if that is indeed even possible), transfer is a chancy event, and we can only talk about the likelihood of transfer. As might be expected, the likelihood and ease of transfer will depend foremost on the dissimilarity, and therefore the extent of mental leap required, between the situation in which the behavior was originally learned and the situation in which it is to be applied. The terms *near transfer* and *far transfer* are used in the literature to indicate such dependence and to distinguish those cases. When the difference between the two tasks is very small, a learner's performance on the target task might appear to be a routine replication of a learned behavior, while if the difference is significant, the ability to apply the old learning is usually described as problem solving; indeed if the target task is vastly different and novel to the performer, its accomplishment would even qualify as evidence of creativity. From this perspective, the distinction between routine and creative work is only a matter of the extent of transfer, and since two tasks are rarely, if ever, exactly alike, all problem-solving behavior can be viewed as a manifestation of a transfer of learning.

As described above, transfer appears to be an event or phenomenon; such a viewpoint focuses on the situations between which the transfer occurs and relates the occurrence or failure of transfer to the training and target tasks and their characteristics. Alternatively, transfer can be construed as an ability or skill in which some individuals are more proficient than others; this viewpoint focuses on the individuals carrying out the transfer and is suitable when examining their preparedness, learning styles, or disposition, which may assist or hinder in transfer. This latter point of view is also pertinent in the educational context where the goal is to inculcate the transfer ability in a learner through instructional programs.

Empirical Evidence for the Occurrence of Transfer

Even though it is pervasive and must be occurring in everyday life, transfer is far from being automatic or guaranteed. Empirical research has found that it has not been so easy to demonstrate transfer experimentally, or to deliberately achieve it in an educational setting through an instructional program. There is a long history, extending over almost a century, of psychologists failing to detect evidence of transfer in carefully controlled laboratory experiments using a deliberately taught skill as the learning experience [1].

A search for explanations behind the failure of empirical studies to detect

TABLE 1. Examples of transfer taken from the domain of RF and microwave engineering.

Type of Transfer	Initial Training Task (or Acquired Skill)	Subsequent Target Task (or Demonstrated Skill)
Direct parallel	Circuit analysis and design of a common-emitter amplifier stage employing a BJT	Circuit analysis and design of a common-source amplifier stage employing a FET
Analogy	Analysis of the conditions for resonance in a taut vibrating string	Deduction of the length of line require for resonance in a transmission line resonator
Context change	Calculating the signal-to-noise ratio degradation in traversing through a lossy linear two-port network	Determination of the signal-to-noise ratio degradation in propagation through a wireless channel in rain
Embedded as a sub-task	Using the impedance transformation properties of a quarter-wavelength long transmission line	Design of multi-section transmission-line impedance transformers of the maximally flat or Chebyshev types
Ease of learning	Learning the use of a computer-aided design (CAD) software	Subsequently learning the use of a new or different CAD software
Negative transfer	Proficiency in low-frequency circuit design, where conductive traces are routinely treated as mere short circuits	Simulation of an RF chip or circuit board during early experience with RF design (resulting in a habitual omission of conductive traces)

transfer suggests that, in addition to reasons that may be specific to the individual studies, there are three broad causes for the earlier negative findings. The first stems from the attempt by experimenters to search for evidence of pure transfer, wherein a leaner spontaneously applies prior learning to a new situation; as a result the studies were often based on experimental protocols in which the learners were given no clues or suggestions to attempt transfer, for fear of contaminating the results by altering the likelihood of transfer. A second reason for failure lies in the selection of learning and target tasks with some superficially common elements, without an adequate analysis of the two tasks to identify the exact type of knowledge that was required to be transferred from the learning to the target task. Finally, a third reason is simply ineffective instruction in the training task.

Transfer is the change, due to the learning resulting from an earlier set of stimuli, in the responses to subsequent stimuli that are novel or different from the original ones.

The factors influencing the likelihood of transfer include the degree of similarity between the training and target tasks; the extent of practice with the training task; the complexity of the tasks as measured for example in terms of the number of required independent steps; the need to simultaneously invoke or juxtapose transfer of prior learning from more than one training task; the presence of a source of interference; the domain or context in which the training and target tasks are embedded; and the nature of the tasks themselves. Given the large number of influencing and interfering factors, the literature on studies of transfer is understandably large, nuanced, and at times seemingly self-contradictory

However, there is reason for educators to be more optimistic. Unlike the laboratory experiments with negative reports on the occurrence of transfer, the educational setting is typically rife with coaching, directing, and deliberate instruction that can augment transfer. Moreover, a technical field like engineering fares better since the learning task and the target task both tend to be well-defined and quantitative, which can increase their degree of similarity, and hence the likelihood of transfer. A good deal of engineering education thus covers areas where transfer can be expected.

The problem for the educators is to find how to deliberately facilitate transfer of knowledge gained via instruction [2]. This article explores ways—other than by asking for gifted students—in which an instructor might attempt to enhance the likelihood of transfer. For this purpose, we focus on the three factors influencing the likelihood of transfer from a training task to a target task in instructional context: the nature of the tasks, the learner's knowledge base, and the type of knowledge involved in transfer. These three factors are successively examined in some detail in the next three sections.

Analyzing the Nature of the Tasks

Studies have shown that certain types of tasks are more amenable to demonstrable transfer, while others seem to be almost immune to training and fail to show evidence of enhanced transfer as a result of instruction [3]. For example, transfer has been experimentally demonstrated, and found to be more likely, for conceptual knowledge, basic skills and routines (such as mathematical operations and graphical savvy), and narrowly framed content-related questions. By contrast, general problem-solving strategies learned in an unrelated context have been shown not to easily transfer to a new context. In seeking to understand the source of this difference, several characteristics and features of the tasks can be pertinent.

In the educational setting, studies showed that many potential instructional activities, even though they may appear to be logical or reasonable choices as learning vehicles or training tasks, failed to result in transfer. Empirical evidence summarized by [4] shows that 1) some transfer does occur; 2) there is a higher likelihood of near transfer of thinking to similar contexts, and lower possibility of far transfer; 3) transfer can indeed occur across knowledge domains; and 4) it does not occur automatically as a result of instruction, but requires a proactive and deliberate effort in instructional design. Where transfer has not resulted despite deliberate instruction, ineffective teaching approach rather than an absence of transfer may be a more likely explanation to consider.

Specifying the extent of commonality between two distinct tasks is not such a straight-forward matter. A given task may be characterized in a variety of ways, for example whether it is purposeful or aimless, requires a factual recall or the performance of a procedure, and is described in abstract or in concrete terms. To be meaningful, the degree of dissimilarity between the training and target tasks must be judged based on the problem structure, conceptual demands of the tasks, or a detailed task analysis, rather than on superficial features such as the presence of a common object or phrase in the task description. Moreover, when the tasks are complex, i.e., when their decomposition or parsing by rational analysis leads to many constituent elements, it is difficult to identify exactly what pieces of knowledge must be carried over from a training task to a target task. For these reasons, a detailed and careful task analysis is an essential part of any study aimed at detecting or demonstrating transfer, identifying the factors influencing transfer, or optimizing instructional design for enhancing transfer.

Such a task analysis is helpful in resolving much of the mystery surrounding the failure of earlier empirical studies to detect or demonstrate transfer. Narrowly defined tasks can show higher levels of transfer, due to the high similarity and the shorter leaps of connections to be made. Learning of such tasks is sometimes described as *training* so as to distinguish it from education where the extent of transfer is more open-ended and can be far reaching.

The Importance of Learner's Knowledge Base

The transfer of knowledge is critically dependent both on what knowledge is present in the learner's memory, and how it is organized. In carrying out the transfer, a learner must select and retrieve the information, already present in his memory as a result of prior learning in an earlier encounter or training task, and then adapt and apply it to the target task. Clearly, the learner must possess both the knowledge to be transferred, as well as the ancillary information required to adapt the retrieved knowledge for the purpose at hand. Three attributes of the knowledge base thus appear to be relevant.

First, it seems logical to suggest that a knowledge base which is large and rich in content will offer more information to select from, and should therefore help increase the likelihood of transfer. Ideally, the enrichment should extend throughout the curriculum, and not just within one subject, so as to enlarge the domain of knowledge from which the learner can be expected to draw. Second, in order to be useful, the retrieved information must be sufficiently complete, detailed, accurate, and in depth to permit its use in a different context, because a superficial or mechanical knowledge will not survive the adaptation; such knowledge is invariably based on conceptual understanding. Finally, the knowledge must be encoded, stored, and organized in the memory such that it is retrievable based on perceived similarities or relationships. Three aspects of the learner's knowledge base are thus significant: its breadth, its depth, and its connectedness. These are the hallmarks of what is colloquially called *deep* learning.

The same knowledge base also serves as the framework for organizing the newly acquired knowledge and linking it to the existing knowledge. The learner accumulates this knowledge base through the acts of reading, listening, and observing, as well as via personal participation in knowledge creation through activities such as quantifying, measuring, and classifying. The knowledge base is therefore greatly influenced by the learner's actions and learning style.

Effective transfer of learning requires the ability to recognize similarities and make connections between the training task and the target task. That ability depends on how the prior learning is stored in human memory, and the richness of the ancillary knowledge base from which to draw the basis for identifying similarities and making connections. For instance, given a circuit diagram, while a mathematician might focus entirely on the geometrical aspects of the circuit layout, an electrical engineer who is knowledgeable about the electrical behavior of circuit components will be able to make more abundant observations of analogies, patterns, equivalences, and regularities, which are the precursors for such tasks as categorization, classification, ordering and mental organization, and helpful in the encoding and retrieval steps of transfer. The breadth of knowledge is therefore important both for application of the knowledge base (transfer) and for growth of the knowledge base (learning).

The need for breadth of learning has far reaching implications in the philosophy and choice of instructional approach. In some problem-based methods of learning, and in curriculum planning based on the technique of concept mapping [5]–[7], the instructional content is limited to that set of theories, principles, and procedures that are immediately needed and useful for solving the problems at hand, with no extra baggage or inert knowledge, thus resulting in demonstrable curricular efficiencies. While such methods offer, along with motivational and other benefits, the advantage of more efficient time use due to their minimalist approach, they may not lead to a broad knowledge base, or be the best suited for long-term transferability of learning. This appears to be a major distinction between university-based courses and the industrial training and short-course programs which have different goals and results, even when they may have the same title, such as "RF Circuit Design."

A similar phenomenon can occur when the students, pressed for time, confine their study to solving the assigned problems, and turn to look up the principles (and pages of the textbook) only when that need arises, in effect employing the assigned problems to guide the scope of study. The risks of this learning strategy are well known: the learning is narrowly focused on immediate needs, and most everything else gets ignored. Such a strategy might be acceptable if the assigned problems were all encompassing, creating a need to practice all the requisite skills and learn the entire gamut of principles; producing such an assignment is not a trivial task, and is prohibitively demanding for most instructors (particularly if a new problem set must be produced each semester to fight the "fraternity files phantom"!). As a result, there are likely to be large holes in the resulting awareness, let alone understanding, of the subject due to wholesale omission of topics, aspects, and applications of the principles of the discipline.

Nature of Transferred Knowledge

To clarify the transfer process, consider an elementary problem, as shown in Table 2. The problem is stated in two forms—in the right column the problem is stated in a physical context, as applied to a real situation. In the left column, the problem is stated in a form where it has already been formulated in an abstract, mathematical form, stripped of any context, and ready for mathematical manipulations. For each problem, some of the most important elements of knowledge required for its solution are listed, and are classified into types of knowledge required. One possible step-by-step method for the solution of the problem is also shown. Actual classroom use by this author has shown that the problem, when couched in an applied context, was perceived as being considerably more difficult, and even those students who possessed each of the elements of knowledge required for its

TABLE 2. Two alternative presentations of an elementary problem.

	In Mathematical Form (Preformulated)	In Physical Context (Applied to a Situation)
Problem Statement	A monochromatic plane electromagnetic wave, propagating in air, has a power density of 1 mW/cm^2. Find the magnitude of the electric field strength in space created by the wave	A microwave oven operates at 2.4 GHz, and the safety regulations limit the human exposure to such radiation at 1 mW/cm^2. Find the largest electric field that can be expected outside an oven that is compliant with the regulations
Advantages of the Form	• Less distraction in conveying the underlying idea • Lower cognitive load • Reinforcement of textbook result through direct use	• Exemplifying the application of underlying idea • Higher motivational value • Practice of formulating the problem in mathematical form
Educational Objective Tested	Procedural knowledge	Situational application of procedural knowledge
Required Elements of Knowledge and Skill	• Procedural knowledge $\mathbf{S} = \mathbf{E} \times \mathbf{H}$ • Declarative knowledge about relationship between **E** and **H** fields in a plane wave $\lvert\mathbf{E}\rvert/\lvert\mathbf{H}\rvert = \eta$ $\angle\theta_{EH} = \pi/2$ rad • Recall of factual knowledge $\eta = 377\ \Omega$ for air	• Identification of parameters given and desired (i.e., initial and goal states) • Idealization of leaked radiation from oven as a plane wave • Correspondence of "largest" E field with "limiting value" of permissible S • All of the elements in the column to the left.
Thought Process During Solution	**Steps in Solution** • $\lvert\mathbf{S}\rvert = \lvert\mathbf{E} \times \mathbf{H}\rvert$ • $\lvert\mathbf{S}\rvert = \lvert E\rvert \cdot \lvert H\rvert \sin\theta_{EH}$ • $\lvert\mathbf{S}\rvert = \lvert E\rvert \cdot \lvert H\rvert$ • $\lvert\mathbf{S}\rvert = \lvert E\rvert^2/\eta$ • $\lvert E\rvert = \sqrt{(\eta S)}$ • $\lvert E\rvert = \sqrt{(377\ \Omega \times 10\ \mathrm{W/m^2})}$	**Hindrances in Solution** • Camouflaging of procedure by context-related distractions, such as ovens and regulations • Superfluous data (operating frequency of oven) • Uncertainty whether radiation leakage from oven can be treated as plane wave • Demand for "largest" (i.e., a bound on) the field (involving an inequality) rather than its magnitude (requiring an equality)

solution in left column were unable to answer the question.

In a typical classroom situation, the mathematical problem in the left column is the learning task, to be used as a learning vehicle, and the physical problem in the right column is the target problem to which previously acquired knowledge must be transferred. The transfer to the target problem is based on both the common declarative knowledge and the common procedural processing shared by the learning and the target problems. The difficulties encountered in the transfer process arise from the dissimilarities between the learning and the target tasks. A detailed analysis of the knowledge required to answer the problem in its physical context shows that the elements of knowledge required for solving the mathematical problem are not sufficient for the physical problem, and the student must deploy additional knowledge. Moreover, it is then necessary to integrate the two sets of knowledge to address the physical problem.

The requisite knowledge for solving a target problem is typically acquired via an earlier exposure to the solution of a learning problem, which clarifies the logic and the sequence of steps involved in the solution. Subject-matter experts save the mental workload and the limited capacity of the short-term memory by lumping together the multiple steps in the chain into a single step, called *chunk*, permitting them to leapfrog. Thus for an expert, the entire line of reasoning used in learning task constitutes a single chunk of information, rather than a procedure. This method of cognitive load reduction gives the experts their advantage over novices.

Model for Describing the Transfer Process

A thorough understanding of how the transfer of knowledge from a training task to a target task occurs would address such fundamental questions as what information from human sensory organs is selected for storage and retention in the human memory; how it is represented, organized and linked in memory; and how the recall of that information is triggered. We presently have very incomplete and speculative theories of transfer, which are woefully inadequate for prescriptive purposes of deliberately facilitating transfer and optimizing instructional design for transfer, or even for predictive purposes, such as what aspects of a problem at hand will trigger the recall of pertinent information from memory. Moreover, the variability among learners, their abilities, and organization of knowledge makes it unlikely that a single approach will be optimal for everyone. Our sketchy understanding of the transfer process is insufficient for even explanatory purposes such as answering why certain kinds of skills are easier to transfer than others, or why some individuals perform better than others at transfer.

However, the progress of educational practice cannot come to a halt until our understanding of human cognition is perfect, and we must make do with the limited extent of current understanding. Although our understanding of the transfer process is very limited, it would be useful and convenient to have a model describing the process for such purposes as identifying the factors that might influence transfer, exploring the reasons why transfer fails to occur in a given situation, or searching for opportunities available to an instructor for potentially facilitating transfer.

One plausible description of the process by which transfer of learning occurs is based on the premise that the information from the training task is stored in the learner's memory encoded in terms of the significant features and characteristics of that task which thus serve as referents; upon recognizing the presence of similar characteristics or features in the target task, a recall of prior learning is triggered. The transfer thus rests on recall by association, with the features or characteristics related to the tasks serving as the basis of association. For cognitive tasks of interest in engineering domains, the referents could include keywords, phrases, or terms; geometrical, spatial, temporal or sequential organization or ordering; cause-and-effect, if-then, or other conditional relationships; and a host of other items that can anchor the information in the memory. Based on this description, the process of transfer can be outlined as a chronological sequence of six stages listed in Table 3. Although this outline of the transfer process is admittedly a post-hoc and conjectural description without an empirical substantiation (and to that extent, all suggestions made in this article could admittedly be viewed as speculative), it is nevertheless a convenient construct, because considerations such as causality (since the stages in the list are chronological) and controllability (an instructor's ability to influence a feature) allow us to narrow down the set of factors to be considered at each stage.

This chronological model of transfer can be used to identify the opportunities available to an instructor, and the type of learning activities potentially helpful, for facilitating transfer of knowledge by learners.

How an Instructor Can Help Facilitate Transfer

Ultimately, the goal of engineering education is to facilitate the transfer of learning from the classroom to the R&D workbench, prototype shop, factory floor, and field installations. Before one can chart the course for reaching such an over-arching goal, it might be useful to first try reaching the more modest goal of achieving successful transfer between one academic subject and another, or even between the topic of one chapter or module

TABLE 3. Chronological sequence of stages leading to the transfer of learning.

Stages in Transfer	Significant Factors and Major Events Occurring at the Stage
1) Pre-Existing State of the Learner	The cognitive preparedness and background of the learner, described by • Domain-specific knowledge already acquired by the learner • Organization and framework of knowledge in the learner's memory • Learner's disposition and personal traits, including perseverance, drive, motivation, interest, mode of thought, style and habits
2) Knowledge Acquisition via the Learning Task	Selective extraction of knowledge from the learning task or problem by • Interpreting the information in the learning task with reference to the existing framework of knowledge • Selecting information based on its relevance or importance to learner • Organizing the selected information into a coherent representation by integrating it within the framework • Construction of new (or extension of existing) knowledge framework within which to embed the new information
3) Storage of Acquired Knowledge for Subsequent Retrieval	Tagging and cataloging of information for accessibility, and its transfer to long-term memory, by • Analysis or parsing of the information to identify its salient features or attributes which serve as referents • Linkage to other information having common referents in the learner's framework of knowledge
4) Dormancy During Intervening Period	Selective retention of knowledge in the long-term memory of the learner, subject to possible alteration by • Reinforcement of knowledge, given appropriate events or opportunities for its activation and use • Loss of acquired knowledge through forgetting, or interference due to subsequently acquired knowledge
5) Comprehension and Classification of Target Task	Characterizing and categorizing the target task by • Analyzing the given information, and developing a mental representation for it • Transformation of the representation to alternative forms using rules prevailing in the domain of knowledge • Classifying the task according to the need for, and applicability of, some prior knowledge believed by the learner to be required for carrying out the task
6) Transfer of Learning to Target Task	Transfer of previously learned knowledge, mediated by • One of the task representations triggering the recognition of the relevance or applicability of some knowledge previously learned in the training task • Retrieval of the relevant parts of stored knowledge based on referents and association • Adapting and applying the retrieved knowledge to the target task by refining or combining it

and the next within a single academic subject. One quickly discovers that this is not so easy. That transfer is not easily accomplished is well known to all teachers who have universally and for a long time lamented the students' inability to answer questions which are very similar to those that the students have previously seen and practiced with.

The chronological model of transfer in Table 3 clarifies the fact that there are many aspects of the transfer process over which an instructor will have little or no influence, such as the learners' pre-existing knowledge and personal traits (stage 1), post-learning stimuli (stage 4), or the target tasks to be confronted by the learner in the future (stages 5 and 6). The instructor's efforts have some bearing on only some of the events during the phases of knowledge acquisition (stage 2) and storage (stage 3). The kind of influence that the instructor can exert in these two stages can be narrowed still further.

In the second stage, the state of a learner's existing knowledge influences the interpretation and incorporation of all new knowledge, and therefore governs all subsequent learning by the learner. An instructor cannot transplant his own organization of information into the learner's memory, because learners do not acquire new knowledge by simply replicating the information presented to them (e.g., by an instructor). Instead, the learners use the input (new information) to construct their own knowledge representation for themselves during the learning process, based (among other factors) on the type of knowledge, their past learning, the context in which the new knowledge is encountered, and the referents with which it is to be anchored in the memory. An instructor can influence the learner's knowledge construction through the choice and design of learning exercises, the sequencing of lessons, context in which the training exercises are couched, and the organizing principle or framework within which they are presented.

In the third stage the learner analyzes the learning situation, task, problem, or its solution, so as to identify the salient features that can serve as referents. The learners must learn to carry out some form of subdivision or parsing of the overall learning task into elements that are meaningful within the mental framework of the learner. The learner would associate the parsed components with an appropriate set of distinguishing attributes, and since the number of components is likely very large, most likely also with a personal hierarchy of significance: i.e., some attributes may appear to the learner to be of crucial importance or enduring, while others would strike as having a marginal significance or being superficial. The learner would then transfer to the long-term memory those features or characteristics judged by him to be important as the referents, with reference to which the associated knowledge can be stored and retrieved. The instructor can potentially influence the knowledge processing at this third stage by exposing the learner to the organizing principles that are more enduring, and the use of more efficient knowledge organizing techniques such as schema.

In summary, the instructor appears to have several opportunities available to potentially influence the learner's transfer ability, such as

- encoding of the learning task via referents
- linkage and extensive cross-coupling of the information within the knowledge framework
- organization of the learned knowledge into a framework of knowledge, for ease of information retrieval, such as by schema
- activating and reinforcing the learned knowledge stored in memory.

Each of these is examined in some detail in the remainder of this article.

Facilitating Information Encoding

The knowledge resulting from a learning task is stored in the memory of the learner for subsequent retrieval and use. Encoding refers to the extraction of some characteristics or features of that knowledge, called referents, selected by the learner based on his own frame of reference, with which the knowledge is associated and tagged when stored in the memory of the learner. Studies show that experts and novices make vastly different choices of encoding, and possibly use different processes—including analysis, parsing, and classification—to arrive at their choices. The choice of encoding in turn influences the efficacy of subsequent retrieval and reuse of that information.

A given learning exercise, problem, or situation can be viewed and classified in a variety of ways depending on the focus. For instance, a learner might construe the problem presented in the right hand column of Table 3 in numerous ways depending on the context in which the problem was encountered and his own point of view or background. Thus an electromagnetic fields expert might classify it as a Poynting theorem problem, relating field intensity and power density; a novice who does not grasp the underlying mathematical structure of the problem may encode it in his memory as a microwave oven problem, to be recalled upon the next encounter with a problem related to microwave ovens; and a bioengineer may store it away as an electromagnetic exposure problem to be recollected when faced with a radiation regulation issue.

For information organization to be efficient for retrieval and reuse, it must be based on enduring rather than ephemeral characteristics that make the stored information accessible, i.e., its encoding is based on the underlying fundamental, rather than the superficial, characteristics and features of the learning exercise. However, an explicit discussion, or even mention, of the encoding issue is rare in the classroom. For each classroom problem, a discussion of "what is this problem an example of" can be a very worthwhile exercise, and would yield additional dividends by making explicit the underlying structure of the problem, and by motivating and prompting the instructor to improve the selection of problems for classroom use.

An instructor can help initiate the students in learning to encode like the experts. A deeper encoding requires critical reading and comprehension, and an instructor can model such expert behavior, in which the instructor extracts the essentials without being distracted by the superficial, and explains to the students how the significance or superficiality was determined. This skill can be exercised by designing assignments in which the essential information is deliberately accompanied with irrelevant information of the kind typically encountered. Problems stated in their natural or applied context provide more opportunities for practicing the extraction of relevant features from the problem statement than do those that are already idealized, formulated, and symbolically represented.

Avoiding Welding Information to Context

The ultimate basis of transfer is the knowledge encoded in the learner's memory that is acquired during the training task. Since this knowledge must have been acquired in some specific context or domain, it would ordinarily remain coupled to that domain through associations, cues, and exemplars. It is clear that the previously learned knowledge must not remain so tightly bound to the training problems that it does not transfer, and must be so organized in the learner's memory that it can be independently retrieved. An instructor can assist in the process in some ways.

One subtle way of enabling a broader encoding is to define terminology in the most general setting that is applicable, such as defining a power gain or noise figure for a linear two-port and not just an amplifier, so that these concepts can be carried over and deployed for circuits other than amplifiers, or even for a wireless channel not normally thought of as a circuit. Table 4 shows an example of the text from a textbook where general results are presented in a narrow context, thus preventing the learner from acquiring the knowledge to transfer them to other settings.

A similar argument applies for employing a more generic and inclusive vocabulary or terminology wherever appropriate, e.g., interconnect line rather than a microstrip line, a semiconductor substrate rather than a silicon substrate, or an impedance transformer rather than a matching network. Beginners who are unsure or unaware of the broader applicability of their learning are usually apt to attach many unnecessarily restrictive qualifiers to their knowledge and thinking unless more generic terms are used. Finally, descriptive names that reveal the function (vector network analyzer) rather than trade names (the Wiltron), acronyms (VNA), and local nicknames (8510) allow a wider linking of the terms in the memory.

The most direct method for emphasizing the broad applicability of ideas is to actually demonstrate that breadth by applications. Major ideas from all courses, not just the one being taught, can and should be deployed frequently. Most instructors are well aware that demonstrating the application of a new concept to some situation can greatly improve the students' clarity of understanding of that concept and that the retention of the concept and the likelihood of its transfer to that application can be strengthened through repetition and practice by the learner. What is even more valuable for enhancing the availability of a concept for transfer beyond the mere repetition and practice is the variety of contexts to which the learner transfers the concept. For example, the concept of a complex permittivity might typically be first encountered in the context of electromagnetic wave propagation in a lossy medium. When complex permittivity is employed in

TABLE 4. Example showing unnecessary welding of concepts to the context.

Presentation as It Appears in a Textbook	**Direct Presentation Revealing Broader Applicability**
"The bandwidth B for an impedance matched antenna operated away from resonance is related to the input VSWR of the antenna and its loaded quality factor Q by: $$Q = \frac{\mathrm{VSWR}-1}{B\sqrt{\mathrm{VSWR}}} \tag{10.1}$$ Here B is the band of frequencies over which the antenna's VSWR (or return loss) is less than some specified maximum value usually taken as 2:1 (or –10 dB)." I.D. Robertson and S. Lucyszyn, eds., *RFIC and MMIC Design and Technology*, (The Institution of Electrical Engineers, London, 2001), p. 430. The description, although correct, 1) conveys the impression that the equation (10.1) has something to do with antennas; 2) does not reveal the source or origin of the equation; 3) does not clearly specify the conditions under which the equation holds; and 4) prevents the learner from applying the equation more widely.	If the driving-point impedance $Z(f) = R(f) + j\,X(f)$, of any linear one-port circuit component, can be approximated as having a real part that is independent of frequency, and an imaginary part that is zero at some frequency f_o, and a linear function of frequency in the neighborhood of f_o, then it can be represented over that neighborhood by the input impedance of a resonant circuit, having a quality factor (the ratio of the energy stored to the energy dissipated per radian) Q given by $$Q = \frac{f_o}{2R} \cdot \frac{dX}{df}. \tag{1}$$ If the reflection coefficient Γ and the VSWR of the one-port are defined with respect to a reference impedance equal to R, the real part of $Z(f)$, then the VSWR remains bounded by a maximum value $\mathrm{VSWR}_{\max}$ over a frequency Interval $(f_o - 1/2\,B)$ to $(f_o + 1/2\,B)$, having a bandwidth $$B = \frac{\mathrm{VSWR}_{\max} - 1}{\sqrt{\mathrm{VSWR}_{\max}}} \cdot \frac{f_o}{Q}. \tag{2}$$

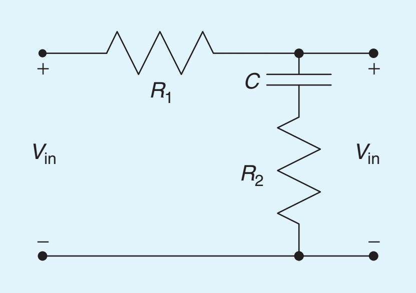


Figure 1. *Equivalent circuit model to illustrate the frequency dependence of permittivity.*

several other contexts, such as calculating loss tangent, attenuation in cables, microwave heating, and attenuation of wireless signals in rain, the concept can become related to many other referents, increasing its transferability.

Furthermore, a new concept provides an opportunity not only to create a forward link in memory by demonstrating its applications but also for creating backward linkages to the concept's prerequisite knowledge, since the concept demonstrates an application of the more elementary underlying knowledge of which it is an outgrowth. In the above example of complex permittivity, a circuit model, such as the one in Figure 1, can be used to exemplify a complex transfer function, its magnitude and phase, and frequency response, thus strengthening the transferability of those more elementary ideas.

Facilitating Information Linkage and Cross-Coupling

Knowledge of isolated facts, concepts, or procedures, which is not richly linked to the rest of the knowledge base, tends to be inert knowledge, and not readily transferable to other domains. In order to make it potentially available for transfer, this knowledge must be linked to information in other domains. An instructor can play a role in such cross-domain linking by being alert to the opportunities for presenting the subject matter in ways that are suggestive of connections with other subjects.

The most obvious opportunity to construct linkages and a framework of factual and conceptual knowledge spanning multiple domains occurs when identical or similar conventions, terminology, or parameters are employed in different fields. However, there is little evidence to show that building such linkages has received a high priority. Consider as an example the definitions of Q as given in textbooks from different knowledge domains within the field of electrical engineering compiled in Figure 2, which is drawn from highly regarded and widely used textbooks (as evidenced by the publication of multiple editions for each book). Each definition rests on parameters taken from a different perspective: driving point impedance, energy, and frequency response of transmission. There is no attempt made in the books, however, to relate the various definitions or to show the unity of the concepts across disciplines. When knowledge presented is fragmented, compartmentalized due

Q as Defined in a Circuit Theory Textbook:

$$Q = \frac{\omega_0 L}{R} \tag{5.1}$$

M. E. Van Valkenburg, Network Analysis, 2nd ed. (Prentice Hall, Englewood Cliffs, N.J., 1964), p. 144.

Q as Defined in a Field Theory Textbook:

$$Q = 2\pi \frac{\text{energy stored in the resonator}}{\text{energy dissipated per cycle}} \tag{5.2}$$

N. N. Rao, Elements of Engineering Electromagnetics, 6th ed. (Prentice Hall, Upper Saddle River, N.J., 2004), p. 628.

Q as Defined in an Optoelectronics Textbook:

$$Q = \frac{\nu_0}{\nu_{1/2}}, \tag{5.3}$$

where

ν_0 = the resonant frequency
$\nu_{1/2}$ = "full-width at half power maximum" (FWHM)

J. T. Verdeyen, Laser Electronics, 3rd ed. (Prentice Hall, Upper Saddle River, N.J., 1995), p. 150.

Unanswered Questions:

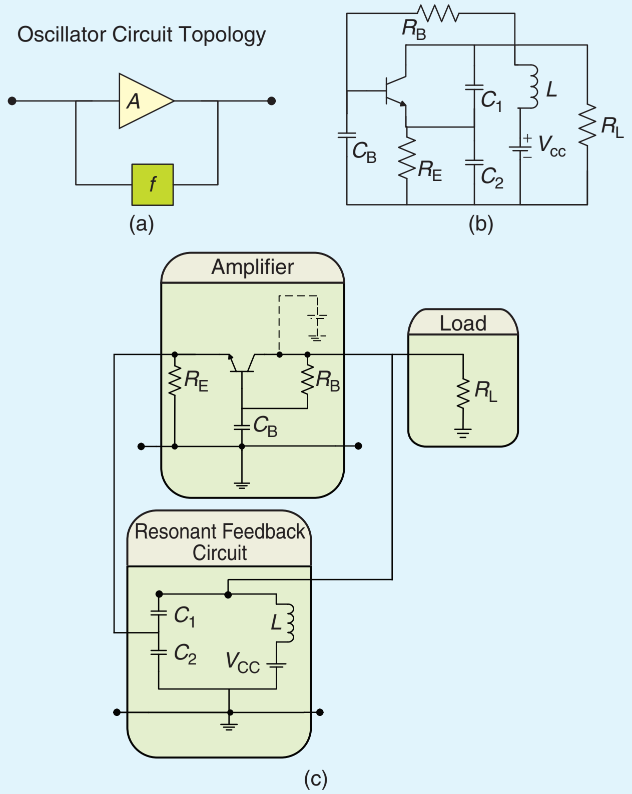
- Are each of the above definitions of Q (i.e., identities), or are some of them expressions (i.e., equalities) applicable under some implicit assumptions?
- Why does the definition of Q in (5.1) restrict itself to the resonant frequency, while that in (5.2) can be used to define Q as a function of frequency?
- Why is it necessary to use different "definitions" for series and parallel tuned circuits?
- Why do some definitions depend on the value of network functions at one frequency while others refer to the sensitivity of the network function values to frequency?

(Note that the three sources cited above are highly successful undergraduate textbooks each having multiple editions, were written by professors in the same department at the same university, and were published by the same publisher.)

Figure 2. *Treatment of Q in different knowledge domains.*

to proliferation of specializations, compressed due to the pressure to deal with explosion of technical knowledge, and rushed due to the urge to cover more material, the instruction suffers from missed opportunities.

Another opportunity for cross-coupling arises from procedural similarities, analogous formulations, and isomorphism of constructs that commonly occur across different subjects. Such parallels also allow the learner to integrate newly acquired knowledge with existing knowledge and to organize it with the aid of the framework of old knowledge already present in the learner's memory. To cross-couple ideas, significant themes from one subject matter domain must be employed and demonstrated to be useful in other domains. Unfortunately, the available typical instructional materials show that they rarely capitalize on such cross-domain coupling. An example is the concept of feedback, usually first encountered in the study of circuits or control systems; as illustrated in the following section, it can be employed in the study of electromagnetics so to take advantage of the understanding of feedback to clarify the concepts of permittivity and skin effect—something that a century of published textbooks on electromagnetic fields appear not to have done. Such a use not only exemplifies an application of the feedback concept, it liberates the concept from the confines of the control system context in the learner's mind, and makes it available to be applied elsewhere; it also creates a link between the two subjects so that an understanding or skill developed in one context can become available in the other.



Understanding the operation and genesis of the circuit is greatly aided by this form of schematic, which makes numerous facts self-evident: that the amplifier is a common-base stage, that the feedback factor is determined entirely by the capacitive voltage divider, that the frequency selectivity is created by the tuned circuit in the feedback block, that varying the coupling of the load will vary the selectivity of this tuned circuit, etc.

Figure 3. *Suggestive schematics. (a) Canonical model of a feedback oscillator circuit. (b) Schematic of Colpitt oscillator as typically drawn in textbooks. (c) Redrawn Colpitt oscillator schematic, having one-to-one correspondence with the canonical feedback model.*

Facilitating Organization of Information

Although we have a very limited understanding of exactly how the information is organized in human long-term memory, we all know that random bits of information are difficult to memorize, retain, and retrieve, while organized information is easier to transfer to, and retain in, long-term memory. Instructional activities and materials therefore need to both organize the content presentation, and teach the learners how to organize the received information.

Most instructors are already well-versed in discipline-specific methods for organizing information. The following is a brief list of some additional general, discipline-independent methods of helping learners improve knowledge organization:

- *Ordering.* Information can be ordered along some dimension or characteristic (such as chronological, spatial, or sequential) for easier recall and transferability.
- *Reflection.* Following the solution of a problem by a reflective discussion to examine its constituent parts (approaches, results, or strategies) helps in unifying them as well as identifying those parts that have a the potential for transfer.
- *Generification.* A generic problem represents an entire class of problems, and a generic method of solution applies to a family of problems, with obvious transferability, although it may require pointing out its application or connection to specific examples.
- *Attention.* Highlighting those aspects of a topic or problem that should receive particular attention can help make them a possible basis for organizing information.
- *Naming.* Assigning a name to an otherwise amorphous set of objects, properties, procedures, etc. creates a handle with which the set can be mentally manipulated.

A useful mental aids to recall is the construction of acronyms; for example, the above five methods of organization, namely Ordering, Reflection, Generification, Attention, and Naming, can be recalled by the acronym ORGAN.

One of the most helpful tools for organizing information that must be committed to long-term memory is to employ schemas, which can impose a structure and framework on otherwise amorphous or disparate pieces of information, and are therefore particularly useful in technical fields that are rife with details. A schema is a pattern, prototype, or template that is useful for expressing relationships among items of various types, somewhat like an organizational chart, and consists of a structured collection of items with abstractly stated relationships among them. It is composed of 1) a set of generic categories, given relatively abstract names or titles so that they can serve as placeholders for more specific or actual members of the category, which may be objects, events, actions, procedures, properties, concepts, goals, etc; and 2) an underlying structure of inter-relationships of various kinds among its members—such as causative, sequential, subordinate, superordinate, controlling, influencing, exemplifying, explaining, qualifying, or characterizing connection between a pair—derived based on experience, observation, or logic. It is useful for capturing and cataloging commonly recurring patterns or ideas, and helps systematize the learning, thinking, or communication about that pattern. Moreover, organizing the information as a schema helps in identifying those aspects of the system that are essentials or pertinent, recalling the organized information or details, and detecting any inconsistencies or omissions of information. When the schema is a misfit, or is cumbersome to apply in a given situation, it reveals overlooked factors, and is usually suggestive of a more appropriate or general schema in a constructive way.

As an illustrative example of schema, consider a feedback loop, as shown in Figure 3(a). Such a structure is encountered by electrical engineering students in circuits and control systems courses, and therefore has the added advantage of being already established in the learners' mind. Organizing still other information in this form thus benefits from taking advantage of pre-existing familiarity for reaching some level of understanding in new domains. For instance, a Colpitt oscillator is known to be a feedback oscillator circuit, but the usual textbook schematic of this circuit shown Figure 3(b) is not drawn in a manner having a one-to-one correspondence with the standard feedback loop block diagram schema. A search through almost 50 textbooks on electronic circuits that discuss this circuit, published over as many years, failed to find even one in which the circuit is drawn in the form shown in Figure 3(c), to clarify the existence of a feedback loop, and at the same time identify the individual blocks of the loop.

The advantages of a schema go deeper than mere visualization. The same feedback loop block diagram can be used to understand many other relationships found in the electrical engineering curriculum, even outside the domain of circuits. Two examples drawn from the curriculum in electromagnetic fields are shown in Figure 4. The first shows how the notion of the permittivity of dielectrics can be understood as a shorthand for relating the input and output variables of a feedback loop, without having to carry out an explicit accounting of the feedback, in effect replacing the feedback loop by a single block. The second shows how the skin effect can be understood to be a consequence of the feedback effect implicit in Ampere's and Faraday's laws, which modifies the relationship between the applied electric field and current density. Once again, such a graphic and illuminating use of the feedback loop schema has not become established in textbooks on electromagnetic fields.

TABLE 5. Schema for organizing knowledge about passive components in RF Integrated circuits.

IC Technology Type and Node: Si CMOS, 0.18 μm					
Type of Component: Resistor					
Type of Component: Diffused					
Construction					
Structure	Layout	Dimensions	Material Properties	Design Variables	Constraints
Attainability					
Range of Values Practicable	Adjustability of Value (Trimming)	Usable Frequency Range	Range of Voltage or Temperature	Chip Area Use Efficiency	Stability with Time or Temperature
Nonidealities					
Imperfections			Parasitics		
Accuracy and Tolerance	Temperature Sensitivity	Nonlinearity	Reactive Parasitics	Losses and Q	Resonances

Schemas are particularly useful where there is much detailed information, and the learners feel lost, or are unsure if they have acquired a sufficient degree of familiarity with the details. One such example occurs in discussions on the subject of the characteristics and design of lumped circuit elements used in radio-frequency integrated circuits (RFICs), commonly presented in most textbooks on the subject. Such discussions include extensive details and characteristics of a variety of passive components—resistors, capacitors, and inductors—fabricated in a variety of forms (interdigital, overlay, multilayer) and with various technologies. As the subject includes numerous and unrelated details, its study often leaves the learners with a feeling of aimless reading and uncertainty about having acquired the requisite level of knowledge. An order can be imposed on the subject by introducing a single common schema, such as the one shown in Table 5, that is broadly applicable to all of such components, and that summarizes their characteristics at an equivalent level of detail for each component. Such a schema is useful as an organizing framework which ensures that the various components are studied at an equal depth of detail and that no significant characteristics are left out; it is also useful as a guide to a study of the subject. Asking the students to locate the information required to complete such a blank schema for each studied component provides a direction and goal to their reading, and develops a sense of the applicability, and relative strengths and weaknesses, of various types of components.

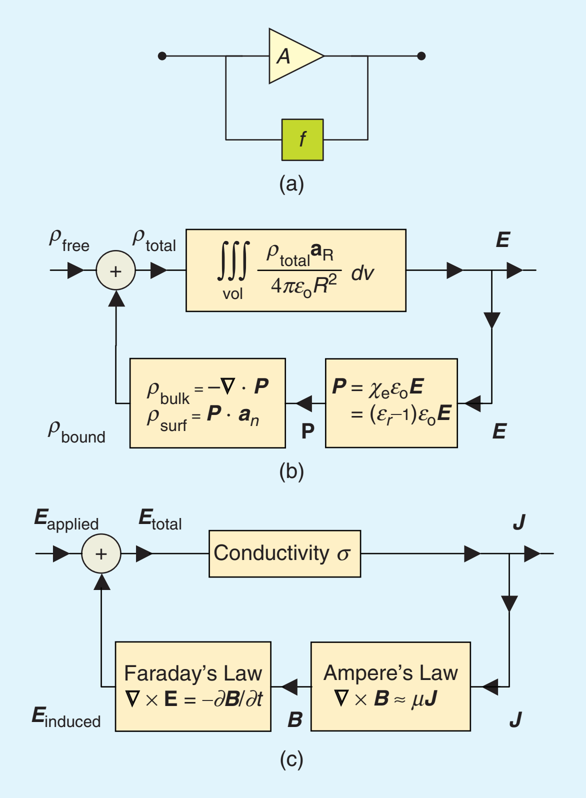


Figure 4. *Presenting electromagnetic concepts in feedback system framework. (a) Canonical form used in learning about feedback systems. (b) The effect of dielectrics on electric field, and relative permittivity. (c) The effect of finite conductivity on electromagnetic waves, and skin effect.*

Activating and Reinforcing Prior Knowledge by Practice

Of all the methods of learning—observed, proposed or speculated—the one that is perhaps the most reliable is emulation; monkey see, monkey do is not just a hollow phrase. Almost the only sure thing that is known to significantly impact transfer is for the instructor to provide many examples and opportunities for practicing the transfer [8]. Experimental evidence has shown that the likelihood of retrieving prior learning increases with the number of times the learners have previously had to retrieve it—the so-called drill effect. Each incident of retrieval, if it occurs under different situations, can broaden the range of stimuli that cause the retrieval to be activated. Moreover, each occurrence of retrieval serves as a model to be emulated on subsequent occasions.

During the fourth stage of dormancy in Table 3, the on-going knowledge construction in the long term memory, and the retrieval of information from it, over time will possibly create opportunities for the reinforcement as well as loss of the learning previously acquired. Perhaps the most relevant among these activities are those that provide the learner with an opportunity to retrieve and use the directly relevant information for a purpose similar to that of target task.

One way of activating the knowledge in the memory is to reuse it in different contexts, or at least in some context different from the one in which it was acquired. This not only illustrates the manner of use, but the linking of the information, and increases the probability of recall. Varying the learning conditions (e.g., contexts or situations under which the training task is performed) further strengthens the learner's ability to reuse the information on a subsequent occasion. Reinforcement via multiple examples in different contexts, at a variety of levels, aids in developing proficiency in transfer; for instance, inductive reasoning observed under different settings enhances the probability that inductive reasoning will be deployed by the learner in a new situation where it has not been used in the learner's experience.

In operational terms, the instructor can enrich the students' learning by providing:

- Explicit discussion of transfer—so that the students have a conscious awareness of the transfer process and can recognize its occurrence.
- Solved examples exemplifying and illustrating transfer, which serve as models and templates for the student to follow.
- Assignments requiring students to invoke transfer skills.
- Examples from across multiple contexts.

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