Understanding How Students Learn and Inferring What They Know: Implications for the Design of Curriculum, Instruction and Assessment

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Introduction

Many educators have argued that the kinds of learning required for the twenty first century go well beyond those required for the last century. In particular, there is a need for all students, not just a select few, to develop their abilities to think, solve problems and become independent learners (e.g., Bruer, 1993; CTGV, 1997; Resnick & Resnick, 1991). This is consistent with recent standards for instruction recommended by groups such as the National Research Council (1996) and the National Council of Teachers of Mathematics (1989, 2000). Perhaps it is not a coincidence that many different "actors" in the educational context have come to share common perspectives about the goals of instruction. Much of the confluence of perspectives can be traced to the past four decades of research on cognition and instruction which has produced an extraordinary outpouring of scientific work on the processes of thinking and learning and on the development of competence in areas of the curriculum. Much of this work has important implications for the design of learning environments and for the nature of the instructional practices that maximize individual and group learning outcomes in such environments. Such knowledge should be of central concern to those involved is designing and developing instructional materials.

In this paper and the accompanying presentation, I provide an overview of the empirical and theoretical foundation for understanding how students learn and for the process of inferring what they know. This knowledge in turn has implications for how to think about the design of curriculum, instruction and assessment. Much of my thinking about these matters is drawn from three recent reports from the National Research Council: *How People Learn: Brain, Mind, Experience and School* (Bransford, Brown, & Cocking, 1999), *How People Learn: Bridging Research and Practice* (Donovan, Bransford & Pellegrino, 1999), and *Knowing What Students Know: The Science and Design of Educational Assessment* (Pellegrino, Chudowsky, & Glaser, 2001).

The Curriculum-Instruction-Assessment Triad

Whether we recognize it or not, three things are central in the educational enterprise – curriculum, instruction, and assessment. The three elements of this triad are linked, although the nature of their linkages and reciprocal influence is often less explicit than it should be. Furthermore, the separate pairs of connections are often inconsistent which can lead to an overall incoherence in the educational enterprise.

Curriculum consists of the knowledge and skills in subject matter areas that teachers teach and students are supposed to learn. The curriculum generally consists of a scope or breadth of content in a given subject area and a sequence for learning. Standards in mathematics and science typically outline the goals of learning, whereas curriculum sets forth the more specific means to be used to achieve those ends. *Instruction* refers to methods of teaching and the learning activities used to help students master the content and objectives specified by a curriculum. Instruction encompasses the activities of both teachers and students. It can be carried out by a variety of methods, sequences of activities, and topic orders. *Assessment* is the means used to measure the outcomes of education and the achievement of students with regard to important competencies. Assessment may include both formal methods, such as large-scale state assessments, or less formal classroom-based procedures, such as quizzes, class projects, and teacher questioning.

A precept of educational practice is the need for alignment among curriculum, instruction, and assessment (e.g., NCTM Assessment Standards, 1995; Webb, 1997). Alignment, in this sense, means that the three functions are directed toward the same ends and reinforce each other rather than working at cross-purposes. Ideally, an assessment should measure what students are actually being taught, and what is actually being taught should parallel the curriculum one wants students to master. If any of the functions is not well synchronized, it will disrupt the balance and skew the educational process. Assessment results will be misleading, or instruction will be ineffective. Alignment is difficult to achieve, however. Often what is lacking is a central theory about the nature of learning and knowing around which the three functions can be coordinated.

Decisions about curriculum, instruction, and assessment are further complicated by actions taken at different levels of the educational system, including the classroom, the school or district, and the state. Each of these levels has different needs, and each uses assessment data in varied ways for somewhat different purposes. Each also plays a role in making decisions and setting policies for curriculum, instruction, and assessment although the locus of power shifts depending on the type of decision involved. Some of these actions emanate from the top down, while others arise from the bottom up. States generally exert considerable influence over curriculum, while classroom teachers have more latitude in instruction. States tend to determine policies on assessment for program evaluation, while teachers have greater control over assessment for learning. This situation means that adjustments must continually be made among curriculum, instruction, and assessment not only horizontally, within the same level (such as within school districts), but also vertically across levels. For example, a change in state curriculum policy will require adjustments in assessment and instruction at all levels.

Most current approaches to curriculum, instruction, and assessment are based on theories and models that have not kept pace with modern knowledge of how people learn (Pellegrino et al., 2001; Shepard, 2000). They have been designed on the basis of implicit and highly limited conceptions of learning. Those conceptions tend to be fragmented, outdated, and poorly delineated for domains of subject matter knowledge. Alignment among curriculum, instruction, and assessment could be better achieved if all three are derived from a scientifically credible and shared knowledge base about cognition and learning in the subject matter domains. The model of learning would provide the central bonding principle, serving as a nucleus around which the three functions would revolve. Without such a central core, and under pressure to prepare students for high-stakes accountability tests, teachers may feel compelled to move back and forth between instruction and external assessment and teach directly to the items on a state test. This approach can result in an undesirable narrowing of the curriculum and a limiting of learning outcomes. Such problems can be ameliorated if, instead, decisions about both instruction and assessment are guided by a model of learning in the domain that represents the best available scientific understanding of how people learn. This brings us to a consideration of what we actually know about the nature of learning and knowing.

Some Important Principles About Learning and Knowing

While there are many important findings about learning and knowing that bear on the design of curriculum, instruction, and assessment, three of the findings described in the *How People Learn* reports are highlighted here. Each has a solid research base to support it, has strong implications for how we teach, and helps us think about ways in which technology assists in the design and delivery of effective learning environments.

The first important principle about how people learn is that students come to the classroom with preconceptions about how the world works which include beliefs and prior knowledge acquired through various experiences. In many cases, the preconceptions include faulty mental models about concepts and phenomena. If their initial understanding is not engaged, they may fail to grasp the new concepts and information that are taught, or they may learn them for purposes of a test but revert to their preconceptions outside the classroom. Research on early learning suggests that the process of making sense of the world begins at a very young age. Children begin in preschool years to develop sophisticated understandings (whether accurate or not) of the phenomena around them (Wellman, 1990). Those initial understandings can have a powerful effect on the integration of new concepts and information. Sometimes those understandings are accurate, providing a foundation for building new knowledge. But sometimes they are inaccurate (Carey and Gelman, 1991). In science, students often have misconceptions of physical properties that cannot be easily observed. In humanities, their preconceptions often include stereotypes or simplifications, as when history is understood as a struggle between good guys and bad guys (Gardner, 1991). A critical feature of effective teaching is that it elicits from students their preexisting understanding of the subject matter to be taught and provides opportunities to build on, or challenge, the initial understanding. James Minstrell, a high school physics teacher, describes the process as follows (Minstrell, 1989: 130-131):

> Students' initial ideas about mechanics are like strands of yarn, some unconnected, some loosely interwoven. The act of instruction can be viewed as helping the students unravel individual strands of belief, label them, and then weave them into a fabric of more complete understanding. Rather than denying the relevancy of a belief, teachers might do better by helping students differentiate their present ideas from and integrate them into conceptual beliefs more like those of scientists.

The understandings that children bring to the classroom can be quite powerful even in the early grades. For example, some children have been found to hold onto their preconception of a flat earth by imagining a round earth to be shaped like a pancake (Vosniadou and Brewer, 1989). This construction of a new understanding is guided by a model of the earth that helps the child explain how people can stand or walk on its surface. Many young children have trouble giving up the notion that one-eighth is greater than one-fourth, because 8 is more than 4 (Gelman & Gallistel, 1978). If children were blank slates, telling them that the earth is round or that one-fourth is greater than one-eighth would be adequate. But since they already have ideas about the earth and about numbers, those ideas must be directly addressed in order to transform or expand them.

Drawing out and working with existing understandings is important for learners of all ages. Numerous research experiments demonstrate the persistence of preexisting understandings even after a new model has been taught that contradicts the naïve understanding. Students at a variety of ages persist in their beliefs that seasons are caused by the earth's distance from the sun rather than by the tilt of the earth (Harvard-Smithsonian Center for Astrophysics, 1987), or that an object that had been tossed in the air has both the force of gravity and the force of the hand that tossed it acting on it, despite training to the contrary (Clement, 1982). For the scientific understanding to replace the naïve understanding, students must reveal the latter and have the opportunity to see where it falls short.

The second important principle about how people learn is that to develop competence in an area of inquiry, students must: (a) have a deep foundation of factual knowledge, (b) understand facts and ideas in the context of a conceptual framework, and (c) organize knowledge in ways that facilitate retrieval and application. This principle emerges from research that compares the performance of experts and novices, and from research on learning and transfer. Experts, regardless of the field, always draw on a richly structured information base; they are not just "good thinkers" or "smart people." The ability to plan a task, to notice patterns, to generate reasonable arguments and explanations, and to draw analogies to other problems, are all more closely intertwined with factual knowledge than was once believed.

But knowledge of a large set of disconnected facts is not sufficient. To develop competence in an area of inquiry, students must have opportunities to learn with understanding rather than memorizing factual content. Key to expertise is a deep understanding of subject matter that transforms factual information into "usable knowledge." A pronounced difference between experts and novices is that experts' command of concepts shapes their understanding of new information: it allows them to see patterns, relationships, or discrepancies that are not apparent to novices. They do not necessarily have better overall memories than other people. But their conceptual understanding allows them to extract a level of meaning from information that is not apparent to novices, and this helps them select and remember relevant information. Experts are also able to fluently access relevant knowledge because their understanding of subject matter allows them to quickly identify what is relevant. Hence, their attention is not overtaxed by complex events.

Geography can be used to illustrate the manner in which expertise is organized around principles that support understanding. A student can learn to fill in a map by memorizing states, cities, countries, etc., and can complete the task with a high level of accuracy. But if the boundaries are removed, the problem becomes much more difficult. There are no concepts supporting the student's information. An expert who understands that borders often developed because natural phenomena (like mountains or water bodies) separated people, and that large cities often arose in locations that allowed for trade (along rivers, large lakes, and at coastal ports) will easily outperform the novice. The more developed the conceptual understanding of the needs of cities and the resource base that drew people to them, the more meaningful the map becomes. Students can become more expert if the geographical information they are taught is placed in the appropriate conceptual framework.

A key finding in the learning and transfer literature is that organizing information into a conceptual framework allows for greater "transfer"; that is, it allows the student to apply what was learned in new situations and to learn related information more quickly. The student who has learned geographical information for the Americas in a conceptual framework approaches the task of learning the geography of another part of the globe with questions, ideas, and expectations that help guide acquisition of the new information. Understanding the geographical importance of the Mississippi River sets the stage for the student's understanding of the geographical importance of the Nile. And as concepts are reinforced, the student will transfer learning beyond the classroom, observing and inquiring about the geographic features of a visited city that help explain its location and size (Holyoak, 1984; Novick and Holyoak, 1991).

A third critical idea about how people learn is that a "metacognitive" approach to instruction can help students learn to take control of their own learning by defining learning goals and monitoring their progress in achieving them. In research with experts who were asked to verbalize their thinking as they worked, it was revealed that they monitored their own understanding carefully, making note of when additional information was required for understanding, whether new information was consistent with what they already knew, and what analogies could be drawn that would advance their understanding. These metacognitive monitoring activities are an important component of what is called adaptive expertise (Hatano, 1990).

Because metacognition often takes the form of an internal conversation, it can easily be assumed that individuals will develop the internal dialogue on their own. Yet many of the strategies we use for thinking reflect cultural norms and methods of inquiry (Hutchins, 1995; Brice-Heath, 1981, 1983; Suina and Smolkin, 1994). Research has demonstrated that children can be taught these strategies, including the ability to predict outcomes, explain to oneself in order to improve understanding, note failures to comprehend, activate background knowledge, plan ahead, and apportion time and memory. Reciprocal teaching, for example, is a technique designed to improve students' reading comprehension by helping them explicate, elaborate, and monitor their understanding as they read (Palincsar and Brown, 1984). The model for using the metacognitive strategies is provided initially by the teacher, and students practice and discuss the strategies as they learn to use them. Ultimately, students are able to prompt themselves and monitor their own comprehension without teacher support.

The teaching of metacognitive activities must be incorporated into the subject matter that students are learning (White & Frederiksen, 1998). These strategies are not generic across subjects, and attempts to teach them as generic can lead to failure to transfer. Teaching metacognitive strategies in context has been shown to improve understanding in physics (White and Frederiksen, l998), written composition (Scardamalia et al., 1984) and heuristic methods for mathematical problem solving (Schoenfeld, 1983, 1984, 1991). And metacognitive practices have been shown to increase the degree to which students transfer to new settings and events (Palincsar and Brown, 1984; Scardamalia et al., 1984; Schoenfeld, 1983, 1984, 1991). Each of these techniques shares a strategy of teaching and modeling the process of generating alternative approaches (to developing an idea in writing or a strategy for problem solving in mathematics), evaluating their merits in helping attain a goal, and monitoring progress toward that goal.

Knowing What Students Know: The Relationship Between Theories of Learning and Knowing and Processes of Assessment

Educators assess students to learn about what they know and can do, but assessments do not offer a direct pipeline into a student's mind. Assessing educational outcomes is not as straightforward as measuring height or weight; the attributes to be measured are mental representations and processes that are not outwardly visible. Thus, an assessment is a tool designed to observe students' behavior and produce data that can be used to draw reasonable inferences about what students know. Deciding what to assess is not as simple as it might appear. Existing guidelines for assessment design emphasize that the process should begin with a statement of the purpose for the assessment and a definition of the content domain to be measured (AERA et al., 1999) (Millman & Greene, 1993). The *Knowing What Students Know* report expands on current guidelines by emphasizing that the targets of inference should also be determined by a cognitive model of learning that describes how people represent knowledge and develop competence in the domain. Starting with a cognitive model of learning is one of the main features that distinguishes the approach to assessment design proposed in *Knowing What Students Know* from current approaches. The cognitive model suggests the most important aspects of student achievement about which one would want to draw inferences and provides clues about the types of assessment tasks that will elicit evidence to support those inferences.

The process of collecting evidence to support inferences about what students know represents a chain of reasoning from evidence about student learning that characterizes all assessments, from classroom quizzes and standardized achievement tests, to computerized tutoring programs, to the conversation a student has with her teacher as they work through an experiment. People reason from evidence every day about any number of decisions, small and large. When leaving the house in the morning, for example, one does not know with certainty that it is going to rain, but may reasonably decide to take an umbrella on the basis of such evidence as the morning weather report and the clouds in the sky.

The process of reasoning from evidence can be portrayed as a triad of three interconnected elements, what we call the *assessment triangle*. The vertices of the assessment triangle represent the three key elements underlying any assessment: a model of student *cognition* and learning in the domain; a set of beliefs about the kinds of *observations* that will provide evidence of students' competencies; and an *interpretation* process for making sense of the evidence. These three elements may be explicit or implicit, but an assessment cannot be designed and implemented without some consideration of each. The three are represented as vertices of a triangle because each is connected to and dependent on the other two. A major tenet of the *Knowing What Students Know* report is that for an assessment to be effective, the three elements must be in synchrony. The assessment triangle provides a useful framework for analyzing the underpinnings of current assessments to determine how well they accomplish the goals we have in mind, as well as for designing future assessments.

The *cognition* corner of the triangle refers to a theory or set of beliefs about how students represent knowledge and develop competence in a subject domain (e.g., fractions). In any particular assessment application, a theory of learning in the domain is needed to identify the set of knowledge and skills that is important to measure for the task at hand, whether that be characterizing the competencies students have acquired thus far or guiding instruction to further increase learning. A central premise is that the cognitive theory should represent the most scientifically credible understanding of typical ways in which learners represent knowledge and develop expertise in a domain. These findings should derive from cognitive and educational research about how people learn, as well as the experience of expert teachers. Use of the term "cognition" is not meant to imply that the theory must necessarily come from a single cognitive research perspective. Theories and data on student learning and understanding can take different forms and encompass several levels and types of knowledge representation that include social and contextual components.

Depending on the purpose for an assessment, one might distinguish from one to hundreds of aspects of student competence to be sampled. These *targets of inference* for a given assessment will be a subset of the larger theory of how people learn the subject matter. Targets for assessment could be expressed in terms of numbers, categories, or some mix; they might be conceived as persisting over long periods of time or apt to change at the next problem step. They might concern tendencies in behavior, conceptions of phenomena, available strategies, or levels of development.

Detailed cognitive models of learning can be used by teachers to diagnose particular difficulties students are having in a specific domain of the curriculum. For example, if the purpose of an assessment is to provide teachers with a tool for determining the most appropriate next steps for arithmetic instruction, the assessment designer should turn to research on children's development of number sense. Case, Griffin, and colleagues have produced descriptions of how young children develop understanding in various mathematical areas (Case, 1996; Case, Griffin, & Kelly, 1999; Griffin & Case, 1997). Drawing from their extensive research on how children develop mathematical understanding as well as the work of other cognitive development researchers -- such as Gelman, Siegler, Fuson, and Piaget -- Case, Griffin and colleagues have constructed a detailed description of how children develop number sense. This theory describes the understandings that children typically exhibit at various stages of development, the ways they approach problems, and the processes they use to solve them. The theory also describes how children typically progress from the novice state of understanding to expertise.

Every assessment is also based on a set of beliefs about the kinds of tasks or situations that will prompt students to say, do, or create something that demonstrates important knowledge and skills. The tasks to which students are asked to respond on an assessment are not arbitrary. They must be carefully designed to provide evidence that is linked to the cognitive model of learning and to support the kinds of inferences and decisions that will be made on the basis of the assessment results. The *observation* vertex of the assessment triangle represents a description or set of specifications for assessment tasks that will elicit illuminating responses from students. In a tutoring session, for example, the observation framework describes what the learner says and does, does not say and do, or says or does with specific kinds of support or scaffolding. In a formal assessment, the observation model describes examinee products, such as written or oral responses, or the choice of a distractor for multiple choice items. In assessment, one has the opportunity to structure some small corner of the world to make observations. The assessment designer can use this capability to maximize the value of the data collected, as seen through the lens of the underlying beliefs about how students learn in the domain.

The tasks selected for observation should be developed with the purpose of the assessment in mind. The same rich and demanding performance task that provides invaluable information to a teacher about his tenth grade class—because he knows they have been studying transmission genetics for the past 6 weeks—could prove impenetrable and worthless for assessing the knowledge of the vast majority of students across the nation. Large-scale assessments generally collect the same kind of evidence for all examinees, thus observations cannot be closely tied to the specific instruction a given student has recently experienced.

Every assessment is also based on certain assumptions and models for interpreting the evidence collected from observations. The *interpretation* vertex of the triangle encompasses all the methods and tools used to reason from fallible observations. It expresses how the observations derived from a set of assessment tasks constitute evidence about the knowledge and skills being assessed. In the context of large-scale assessment, the interpretation method is usually a statistical model, which is a characterization or summarization of patterns one would expect to see in the data given varying levels of student competency. In the context of classroom assessment, the interpretation is often made less formally by the teacher, and is usually based on an intuitive or qualitative model rather than a formal statistical one.

A crucial point is that each of the three elements of the assessment triangle not only must make sense on its own, but also must connect to each of the other two elements in a meaningful way to lead to an effective assessment and sound inferences. Thus to have an effective assessment, all three vertices of the triangle must work together in synchrony. Central to this entire process, however, are theories and data on how people learn and what students know as they develop competence in aspects of the curriculum.

Unfortunately, many instructional designers and cognitive researchers eschew thinking about matters of assessment. They typically pay little attention to assessment in the design of their materials and methods of instruction. This major oversight can often be explained by the misconception that assessment stands apart from the dynamics of learning and teaching -- rather assessment is mistakenly interpreted to mean an external, largely summative "testing" activity. Ignoring matters of assessment as integral to the processes of learning and teaching is not acceptable if we take seriously the need for curriculum, instruction and assessment to work together as a whole and for all three to be driven by common underlying theories and research about the nature of learning and knowing.

Some Implications for the Processes of Teaching and the Design of Instruction and Assessment

The core learning and assessment principles described above, simple though they may seem, have profound implications for the enterprise of teaching and for the design of instruction and assessment. What follows are just a few of those implications:

To support student learning, teachers must draw out and work with the preexisting understandings that their students bring with them. This requires that the model of the child as an empty vessel to be filled with knowledge provided by the teacher must be replaced. Instead the teacher must actively inquire into students' thinking, creating classroom tasks and conditions under which student thinking can be revealed. Students' initial conceptions then provide the foundation on which the more formal understanding of the subject matter is built. The roles for assessment must be expanded beyond the traditional concept of "testing." The use of frequent formative assessment helps make students' thinking visible to themselves, their peers, and their teacher. This provides feedback that can guide modification and refinement in thinking. Given goals of learning with understanding, assessments must tap understanding rather than the mere ability to repeat facts or perform isolated skills.

Teachers must teach some subject matter in depth, providing many examples in which the same concept is at work and providing a firm foundation of factual knowledge. This requires that superficial coverage of all topics in a subject area must be replaced with in-depth coverage of fewer topics that allows key concepts in that discipline to be understood. The goal of coverage need not be abandoned entirely, of course. But there must be a sufficient number of cases of in-depth study to allow students to grasp the defining concepts in specific domains within a discipline. Moreover, in-depth study in a domain often requires that ideas be carried beyond a single school year before students can make the transition from informal to formal ideas. This requires active coordination of the curriculum across school years, something which is typically done only at a very shallow and superficial level which typically includes overlapping or repeated topic coverage without any serious attempt to build upon the prior concepts and information.

Assessment at the classroom level as well as for purposes of accountability (e.g., statewide assessments) must test deep understanding and not just surface knowledge. By deep understanding we mean evidence of an understanding of conceptual organization and conceptual relationships as well as the ability to apply knowledge of a topic, wheras surface knowledge includes disconnected simple factual or procedural knowledge based primarily on topic memorization. Assessment tools are often the standard by which teachers are held accountable. A teacher is put in a bind if she or he is asked to teach for deep conceptual understanding, but in doing so produces students who perform more poorly on standardized tests. Unless new assessment tools, at the classroom and district or state levels, are aligned with new approaches to teaching, the latter are unlikely to muster support among the schools and their constituent parents. This goal is as important as it is difficult to achieve.

The teaching of metacognitive skills should be integrated into the curriculum in a variety of subject areas. Because metacognition often takes the form of an internal dialogue, many students may be unaware of its importance unless the processes are explicitly emphasized by teachers. An emphasis on metacognition needs to accompany instruction in each of the disciplines because the type of monitoring required will vary. In history, for example, the student might be asking himself, “who wrote this document, and how does that affect the interpretation of events,” while in physics the student might be monitoring her understanding of the underlying physical priniciple at work. Integration of metacognitive instruction with discipline-based learning can enhance student achievement and develop in students the ability to learn independently. It should consciously be incorporated into curricula across disciplines and age levels.

A benefit of focusing on knowledge about how people learn is that it helps us think in more principled ways about critical issues such as the selection of instructional strategies. Consider the many possible instructional strategies that are debated in education circles and the media. Often the nature of the debate is posed as a better-than or worse-than set of all-or-none propositions. They include implicit or explict contrasts among lecture-based teaching, text-based teaching, inquiry-based teaching, technology-enhanced teaching, teaching organized around individuals versus cooperative groups, and so forth. Are some of these teaching techniques better than others? Is lecturing a poor way to teach, as many seem to claim? Is cooperative learning good? Does technology-enhanced teaching help achievement or hurt it?

Research and theory on *How People Learn* suggests that these are the wrong questions. Asking, which teaching technique is best is analogous to asking which tool is best--a hammer, a screwdriver, a plane, or pliers. In teaching as in carpentry, the selection of tools depends on the task at hand and the materials one is working with. Books and lectures can be wonderfully efficient modes of transmitting new information for learning. They can excite the imagination, and hone students’ critical faculties. But one would choose other kinds of activities to elicit from students their preconceptions and level of understanding, or to help them see the power of using metacognitive strategies to monitor their learning. Hands-on activities and experiments can be a powerful way to ground emergent knowledge, but they do not alone evoke the underlying conceptual understandings that aid generalization. There is no universal best teaching practice.

If, instead, the point of departure is a core set of learning principles, then the selection of teaching strategies, mediated, of course, by subject matter, age and grade level, and desired outcome, can be purposeful. The many possibilities then become a rich set of opportunities from which a teacher constructs an instructional program rather than a chaos of competing alternatives.

Focusing on how people learn can help teachers move beyond various either-or dichotomies that have plagued the field of education. One such issue is whether schools should emphasize “the basics” or teach thinking and problem-solving skills. Both are necessary. Students’ abilities to acquire organized sets of facts and skills are actually enhanced when they are connected to meaningful problem-solving activities, and when students are helped to understand why, when, and how those facts and skills are relevant. And attempts to teach thinking skills without a strong base of factual knowledge do not promote problem-solving ability or support transfer to new situations.

Principles for the Design of Learning Environments and Instructional Materials and Practices

Findings from contemporary research and theory on learning and assessment, such as those described above and contained in the *How People Learn* and *Knowing What Students Know* reports, suggest four important characteristics of powerful and effective learning environments. These characteristics should influence the design of instructional materials and practices.

Effective learning environments are knowledge-centered. Attention is given to what is taught -- the central subject matter concepts; why it is taught -- to support “learning with understanding” rather than merely remembering; and what competence or mastery looks like.

Effective learning environments are learner-centered. Educators must pay close attention to the knowledge, skills, and attitudes that learners bring into the classroom. This incorporates preconceptions regarding subject matter and occupational domains and it also includes a broader understanding of the learner. Teachers in learner-centered environments pay careful attention to what students know as well as what they don't know, and they continually work to build on students' strengths.

Effective learning environments are assessment-centered. Especially important are efforts to make students' thinking visible through the use of frequent formative assessment. This permits the teacher to grasp the students' preconceptions, understand where students are on the "developmental corridor" from informal to formal thinking in a domain, and design instruction accordingly. They help both teachers and students monitor progress.

Effective learning environments are community-centered. This includes the development of norms for the classroom and workplace, as well as connections to the outside world, that support core learning values. These communities can build a sense of comfort with questioning rather than knowing the answers and can develop a model of creating new ideas that builds on the contributions of individual members.

Four principles for the design of instruction are consistent with the ideas just mentioned. These four principles are critically important for achieving learning with understanding.

- To establish knowledge centered elements in a learning environment, *instruction is organized around meaningful problems with appropriate goals*.
- To support a learner centered focus, *instruction must provide scaffolds for solving meaningful problems and supporting learning with understanding*.
- To support assessment centered activities, *instruction provides opportunities for practice with feedback, revision, and reflection*.
- To create community in a learning environment, *the social arrangements of instruction must promote collaboration and distributed expertise, as well as independent learning*. .

<u>*Instruction is organized around the solution of meaningful problems*</u>. When students acquire new information in the process of solving meaningful problems, they are more likely to see its potential usefulness than when they are asked to memorize isolated facts and procedures. Meaningful problems also help students overcome the "inert knowledge" problem defined by Whitehead (1929) as knowledge previously learned but not remembered in situations where it would be potentially useful. Seeing the relevance of information to everyday problems helps students understand when and how the information may be useful.

When students see the usefulness of information, they are also more motivated to learn (McCombs, 1991, 1994). Research on the relationship between interest and learning indicates that personal interest in a topic or domain positively impacts academic learning in that domain (Alexander, Kulikowich & Jetton, 1994). New approaches to motivation emphasize motivational enhancement through authentic tasks that students perceive as real work for real audiences. This emphasis contrasts with earlier emphases on elaborate extrinsic reinforcements for correct responding (see for discussion Collins, 1996). Problem solving is at the core of inquiry- or project-based learning. Students will work on problems that are interesting and personally meaningful (Brown & Campione, 1994; CTGV, 1997; Hmelo & Williams, 1998; Resnick & Klopfer, 1989). Several contemporary educational reform efforts use dilemmas, puzzles, and paradoxes to stimulate learners' interests in the topic of study (Brown & Campione, 1994, 1996; CTGV, 1997; Goldman, et al., 1996; Lamon, et al., 1996; Scardamalia, Bereiter, & Lamon, 1994; Secules, et al., 1997; Sherwood, et al., 1995). Problem-based learning has also been a central concept in many areas of occupational and professional training such as medicine, law, and engineering.

One major challenge for inquiry-based learning environments is developing problems that are rich and complex enough to engage students in the kinds of sustained inquiry that will allow them to deeply understand important new concepts. Bringing complex problems into the instructional setting is an important function of technology. Unlike problems that occur in the real world, problems that are created with graphics, video, and animation can be explored again and again. These multimedia formats capture interest and provide information in the form of sound and images that is not available in text-based problems and vignettes. Multimedia formats are more easily understood and allow the learner to concentrate on high level processes such as identifying problem solving goals or making important inferences (Sharp, Bransford, Goldman, Risko, Kinzer, & Vye, 1995).

Although technology-based problem environments come in many forms, an important characteristic is that they are under the learner's control. Problems presented via the World Wide Web or in hypermedia allow students to search easily for the parts that interest them most. Exploratory environments such as "microworlds" or simulations allow students to carry out actions, immediately observe the results, and attempt to discover the rules that govern the system's behavior. No matter what form of technology is involved, the student is primarily responsible for deciding how to investigate the problem and the technology creates an environment in which flexible exploration is possible.

Instruction provides scaffolds for achieving meaningful learning. The preceding briefly describes the benefits of giving students the opportunity and responsibility of exploring complex problems on their own. This is clearly a way to support the implementation of knowledge centered elements in a learning environment. The mere presence of these opportunities, however, does not lead to learning with understanding. Because of the complexity of many realistic problems and the inexperience of students, scaffolds must be provided to help students carry out the parts of the task that they cannot yet manage on their own. Cognitive scaffolding assumes that individuals learn through interactions with more knowledgeable others, just as children learn through adult-child interactions (Bakhtin, 1981; Bruner, 1983; Vygotsky, 1962). Knowledgeable experts model good thinking, provide hints, and prompt students who cannot "get it" on their own. Cognitive scaffolding can be realized in a number of ways. Collins, Brown, and Newman (1989) suggest modeling and coaching by experts, and providing guides and reminders about the procedures and steps that are important for the task.

Technologies can also be used to scaffold the solution of complex problems and projects by providing resources such as visualization tools, reference materials, and hints. Multimedia databases on CD-ROM or on the World Wide Web provide important resources for students who are doing research. Technology can also help learners visualize processes and relationships that are normally invisible or difficult to understand.

Instruction provides opportunities for practice with feedback, revision, and reflection. Feedback, revision, and reflection are aspects of metacognition that are critical to developing the ability to regulate one's own learning. Many years ago, Dewey (1933) noted the importance of reflecting on one's ideas, weighing our ideas against data and our predictions against obtained outcomes. In the context of teaching, Schön (1983, 1988) emphasizes the importance of reflection in creating new mental models. Content-area experts exhibit strong self-monitoring skills that enable them to regulate their learning goals and activities. Self-regulated learners take feedback from their performance and adjust their learning in response to it. Self-monitoring depends on deep understanding in the domain because it requires an awareness of one's own thinking, sufficient knowledge to evaluate that thinking and provide feedback to oneself, and knowledge of how to make necessary revisions. In other words, learners cannot effectively monitor what they know and make use of the feedback effectively unless they have deep understanding in the domain. The idea that monitoring is highly knowledge dependent creates a dilemma for novices. How can they regulate their own learning without the necessary knowledge to do so? Thus, the development of expertise requires scaffolds for monitoring and self-regulation skills so that deep understanding and reflective learning can develop hand-in-hand.

Analyses of expert performance indicate that the development of expertise requires considerable practice over a long period of time (e.g., Bereiter & Scardamalia, 1993; Glaser & Chi, 1988). Cycles of feedback, reflection, and opportunities for revision provide students with opportunities to practice using the skills and concepts they are trying to master. Cognitive theories of skill acquisition place importance on practice because it leads to fluency and a reduction in the amount of processing resources needed to execute the skill (e.g., Anderson, 1983; Schneider, Dumais, & Shiffrin, 1984; Schneider & Shiffrin, 1977). Practice with feedback produces better learning than practice alone. Unless learners get feedback on their practice efforts, they will not know how to adjust their performance to improve.

There are now multiple examples of advanced uses of technology to support a wide range of formative assessment practices in the classroom. They include exciting new technology-based methods such as the "Diagnoser" software for physics and mathematics learning developed by Hunt & Minstrell (1994), the work by Landauer, Foltz and Kintsch (1998) using "Latent Semantic Analysis" for scoring essays, and very exciting work by Ron Stevens and his colleagues (Hurst, Casillas, & Stevens, 1998) using the IMMEX system for providing feedback on problem solving. Many of these examples, as well as very sophisticated work in intelligent tutoring systems, make use of variety of feedback processes that are consistent with the design principles mentioned earlier.

The social arrangements of instruction promote collaboration and distributed expertise, and well as independent learning. ¨ The view of cognition as socially shared rather than individually owned is an important shift in the orientation of cognitive theories of learning. It reflects the idea that thinking is a product of several heads in interaction with one another (Bereiter, 1990; Hutchins, 1991). In the theoretical context of cognition-as-socially-shared, researchers have proposed having learners work in small groups on complex problems as a way to deal with complexity. Working together facilitates problem solving and capitalizes on distributed expertise (Barron, 1991; Brown & Campione, 1994, 1996; CTGV, 1992a,b,c, 1993a,b, 1994a; Pea, 1993; Salomon, 1993; Yackel, Cobb, & Wood, 1991). Collaborative environments also make excellent venues for making thinking visible, generating and receiving feedback, and revising thinking (Barron et al., 1995; CTGV, 1994a; Hatano & Inagaki, 1991; Vye et al., 1997, 1998).

A number of technologies support collaboration by providing venues for discussion and communication among learners. Communal databases and discussion groups make thinking visible and provide students with opportunities to give and receive feedback, often with more reflection because the comments are written rather than spoken. Networked and Web-based communications technologies such as E mail, List Serves, and more sophisticated knowledge building software such as Speak Easy and Knowledge Forum (Scardamalia & Bereiter, 1994) can also help students form a community around important ideas. Such technology helps capture ideas that otherwise can be ephemeral and it supports communication that is asynchronous as well as synchronous.

Concluding Comments and Directions for Application

This paper began with the idea that three critical elements of the educational enterprise – curriculum, instruction and assessment – represent an integrated system. Often, however, such integration is lacking or if there is some degree of integration it is driven by simplistic and outmoded conceptions of the nature of learning and knowing. Contemporary research and theory on how people learn, the nature of knowing, and how we can know what students know offers us a richer perspective by which to approach issues of designing contemporary curricula, instructional practices and materials, and assessments. There are a variety of ways in which we can envision using such knowledge. Two broad approaches are outlined below: (1) evaluating the conceptual and operation base of existing curricula and materials, and (2) designing new curricula and materials and evaluating their effectiveness.

Evaluating Existing Materials. We need to consider using the principles in the *How People Learn* and *Knowing What Students Know* reports as a lens through which to evaluate existing education practices and policies. *How People Learn* and *Knowing What Students Know* emphasize that many existing educational materials and practices are inconsistent with what is known about learning. Teams of discipline-specific experts, researchers in pedagogy and cognitive science, and teachers need to review widely used curricula, as well as curricula that have a reputation for teaching for understanding. The envisioned activity could involve two stages; these might be conducted together in a project, or as sequential projects.

Stage 1: Curricula and their companion instructional techniques and assessments should be evaluated with careful attention paid to alignment with the principles of learning outlined in *How People Learn*. The review might include consideration of the extent to which the curriculum emphasizes depth over breadth of coverage; the effectiveness of the opportunities provided to grasp key concepts related to the subject matter; the extent to which the curriculum provides opportunities to explore preconceptions about the subject matter; the adequacy of the factual knowledge base provided by the curriculum; the extent to which formative assessment procedures are built into the curriculum, and the extent to which accompanying summative assessment procedures measure understanding and ability to transfer rather than memory of fact.

The features that support learning should be highlighted and explained, as should the features that are in conflict. Such work should accomplish two goals. First, it should identify examples of curriculum components, instructional techniques, and assessment tools that incorporate the principles of learning. Second, the explication of features that support or conflict with the principles of learning should be provided in sufficient detail and in a format that allows the effort to serve as a learning device for those in the education field who choose and use teaching and assessment tools. As such, it could serve as a reference document when new curricula and assessments are being considered.

Stage 2: Curricula that are considered promising should be evaluated to determine their effectiveness when used in practice. Curricula that are highly rated on paper may be very difficult for teachers to work with, or in the light of classroom practice may fail to achieve the level of understanding for which they are designed. Measures of student achievement take center stage in this effort. Through the lens of *How People Learn* and *Knowing What Students Know,* achievement is indicated not only by a command of factual knowledge, but by a student's conceptual understanding of subject matter, and the ability to apply those concepts to future learning of new, related material. Where existing assessments do not measure conceptual understanding and knowledge transfer, this stage will require development and testing of such measures. In addition to achievement scores, feedback from teachers and curriculum directors who use the materials would provide additional input for stage 2.

Ideally, the review of curricula would take place at several levels: at the level of curriculum units, which may span several weeks of instructional time; at the level of semester-long and year-long sequences of units; and at the level of multiple grades, so that students have chances to progressively deepen their understanding over a number of years. The curricula reviewed should not be limited to those that are print based.

Developing New Materials. As an extension of the ideas mentioned above, or in some cases as a substitute, we also need to focus on the development and evaluation of new curriculum and assessment materials that reflect the principles of learning and assessment outlined in *How People Learn* and *Knowing What Students Know.* Such development needs to be done by teams of disciplinary experts, cognitive scientists, curriculum developers, and expert teachers. Ideally, activity of this type will begin with existing curricula and modify them to better reflect key principles of learning. In some cases, however, exemplary curricula for particular kinds of subject matter may not exist, so the teams will need to create them. The curricula should be designed to support learning for understanding; they will presumably emphasize depth over breadth. The designs should engage students' initial understanding, promote construction of a foundation of factual knowledge in the context of a general conceptual framework, and encourage the development of meta-cognitive skills.

Companion teacher materials for a curriculum should include a "meta-guide" that explains its links to principles of learning, reflects pedagogical content knowledge concerning the curriculum, and promotes flexible use of the curriculum by teachers. The guide should include discussion of expected prior knowledge (including typical preconceptions), expected competencies required of students, ways to assess prior knowledge, and ways to carry out formative assessments. Potentially excellent curricula can fail because teachers are not given adequate support to use them. While instructional guides cannot replace teacher training efforts, the meta-guide should be both comprehensive and user-friendly to supplement those efforts. Finally, both formative and summative tests of learning and transfer should be proposed as well.

Once developed, it is clear that field-testing of the curricula will be needed in order to amass data on student learning and teacher satisfaction, identifying areas for improvement. Clearly, it is easier to field-test short units rather than longer ones. Ideally, different research and development groups that are focusing on similar topics across different age groups (e.g., algebra in elementary, middle, and high school) might work to explore the degree to which each of the parts seems to merge into a coherent whole. Finally, careful attention must be paid to the criteria used to evaluate the learning that is supported by the materials and accompanying pedagogy. Achievement should measure understanding of concepts and ability to transfer learning to new, related areas.

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