6 Cognitive Apprenticeship

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Throughout most of history, teaching and learning have been based on apprenticeship. Children learned how to speak, grow crops, construct furniture, and make clothes. But they didn't go to school to learn these things; instead, adults in their families and in their communities showed them how, and helped them do it. Even in modern societies, we learn some important things through apprenticeship: we learn our first language from our families, employees learn critical skills on the job, and scientists learn how to conduct research by working side by side with senior scientists as part of their doctoral training. But for most other kinds of knowledge, schooling has replaced apprenticeship. The number of students pursuing an education has dramatically increased in the past two centuries, and it gradually became impossible to use apprenticeship on the large scale of modern schools. Apprenticeship requires a very small teacher-to-learner ratio that is not realistic in the large educational systems of modern economies.

Even in modern societies, when someone has the resources and a strong desire to learn, they often hire a coach or tutor to teach them by apprenticeship – demonstrating that apprenticeship continues to be more effective even in modern societies. If there were some way to tap into the power of apprenticeship without incurring the costs of hiring a teacher for every two or three students, it could be a powerful way to improve schools. In the 1970s and 1980s, researchers in computers and education were studying how technology could help to transform schooling. In a series of articles (e.g., Collins & Brown, 1988; Collins, Brown, & Newman, 1989), we explored how to provide students with apprenticeship-like experiences, providing the type of close attention and immediate response associated with apprenticeship.

From Traditional to Cognitive Apprenticeship

In her study of a tailor shop in Africa, Lave (1988) identified the central features of traditional apprenticeship. First, traditional apprenticeship focuses on specific methods for carrying out tasks. Second, skills are instrumental to the accomplishment of meaningful real-world tasks, and learning is embedded in a social and functional context, unlike schooling where skills and knowledge are usually abstracted from their use in the world. Apprentices learn domain-specific methods through a combination of what Lave called observation, coaching, and practice. In this sequence of activities, the apprentice repeatedly observes the master modeling the target process, which usually involves a number of different but interrelated subskills. The apprentice then attempts to execute the process with guidance and coaching from the master. A key aspect of coaching is guided participation: the close support, which the master provides, to help the novice complete an entire task, even before the novice has acquired every skill required. As the learner develops the needed skills, the master reduces his or her participation, providing fewer hints and less feedback to the learner. Eventually, the master fades away completely, when the apprentice has learned to smoothly execute the whole task.

Of course, most people think of traditional trades when they hear the term *apprenticeship* – like shoemaking or farming. We realized that the concept of apprenticeship must be updated to make it relevant to modern subjects like reading, writing, and mathematics. We called this updated concept "cognitive apprenticeship" to emphasize two issues (Brown, Collins, & Duguid, 1989; Collins, Brown, & Newman, 1989).

First, the term *apprenticeship* emphasizes that cognitive apprenticeship was aimed primarily at teaching the processes that experts use to handle complex tasks. Like traditional apprenticeship, cognitive apprenticeship emphasizes that knowledge must be used in solving real-world problems. Conceptual knowledge is learned in a variety of contexts, encouraging both a deeper understanding of the meaning of the concepts themselves, and a rich web of memorable associations between them and the problem-solving contexts. This dual focus on expert processes and learning in context are shared by both traditional apprenticeship and cognitive apprenticeship.

Second, the term *cognitive* emphasizes that the focus is on cognitive skills, rather than physical ones. Traditional apprenticeship evolved to teach domains in which the target skills are externally visible, and thus readily available to both student and teacher for observation, refinement, and correction, and bear a transparent relationship to concrete products. But given the way that most subjects are taught in school, teachers cannot make fine adjustments in students' application of skill and knowledge to tasks, because they can't see the cognitive processes in students' heads. By the same token, students do not usually have access to the problem-solving processes of instructors as a basis for learning through observation. Before apprenticeship methods can be applied to learn cognitive skills, the learning environment has to be changed to make these thought processes visible. Cognitive apprenticeship is designed to bring these cognitive processes into the open, where students can observe and practice them.

There are two major differences between cognitive apprenticeship and traditional apprenticeship. First, because traditional apprenticeship is set in the workplace, the problems and tasks given to learners arise not from pedagogical concerns, but from the demands of the workplace. Because the job selects the tasks for students to practice, traditional apprenticeship is limited in what it can teach. Cognitive apprenticeship differs from traditional apprenticeship in that tasks and problems are chosen to illustrate the power of certain techniques, to give students practice in applying these methods in diverse settings, and to increase the complexity of tasks slowly, so that component skills can be integrated. In short, tasks are sequenced to reflect the changing demands of learning.

Second, whereas traditional apprenticeship emphasizes teaching skills in the context of their use, cognitive apprenticeship emphasizes generalizing knowledge so that it can be used in many different settings. Cognitive apprenticeship extends practice to diverse settings and articulates the common principles, so that students learn how to apply their skills in varied contexts.

A Framework for Cognitive Apprenticeship

Cognitive apprenticeship focuses on four dimensions that constitute any learning environment: content, method, sequence, and sociology (see Table 6.1).

Content

Recent cognitive research has begun to differentiate the types of knowledge required for expertise. Of course, experts have to master the explicit concepts, facts, and procedures associated with a specialized area – what researchers call *domain knowledge*. This is the type of knowledge that is generally found in school textbooks, lectures, and demonstrations. Examples of domain knowledge in reading are vocabulary, syntax, and phonics rules.

Domain knowledge is necessary but not sufficient for expert performance. In addition, experts know how use their domain knowledge to solve real-world problems. We call this second kind of knowledge *strategic knowledge.* Research has identified three kinds of strategic knowledge:

1. *Heuristic strategies* are generally effective techniques and approaches for accomplishing tasks that might be regarded as "tricks of the trade"; they don't always work, but when they do, they are quite helpful. Most heuristics are tacitly acquired by experts through the practice of solving problems. However, there have been noteworthy attempts to address heuristic learning explicitly (Schoenfeld, 1985). In mathematics, a heuristic for solving problems is to try to find a solution for simple cases and see if the solution generalizes.
2. *Control strategies*, or *metacognitive strategies*, control the process of carrying out a task. Control strategies have monitoring, diagnostic, and remedial components; decisions about how to proceed in a task depend

Table 6.1. *Principles for designing cognitive apprenticeship environments*

Content	*types of knowledge required for expertise*
Domain knowledge	subject matter specific concepts, facts, and procedures
Heuristic strategies	generally applicable techniques for accomplishing tasks
Control strategies	general approaches for directing one's solution process
Learning strategies	knowledge about how to learn new concepts, facts, and procedures
Methods	*ways to promote the development of expertise*
Modeling	teacher performs a task so students can observe
Coaching	teacher observes and facilitates while students perform a task
Scaffolding	teacher provides supports to help students perform a task
Articulation	teacher encourages students to verbalize their knowledge and thinking
Reflection	teacher enables students to compare their performance with others
Exploration	teacher invites students to pose and solve their own problems
Sequencing	*keys to ordering learning activities*
Increasing complexity	meaningful tasks gradually increasing in difficulty
Increasing diversity	practice in a variety of situations to emphasize broad application
Global to local skills	focus on conceptualizing the whole task before executing the parts
Sociology	*social characteristics of learning environments*
Situated learning	students learn in the context of working on realistic tasks
Community of practice	communication about different ways to accomplish meaningful tasks
Intrinsic motivation	students set personal goals to seek skills and solutions
Cooperation	students work together to accomplish their goals

on an assessment of one's current state relative to one's goals, on an analysis of current difficulties, and on the strategies available for dealing with difficulties. For example, a comprehension monitoring strategy might be to try to state the main point of a section one has just read; if one cannot do so, it might be best to reread parts of the text.

3. *Learning strategies* are strategies for learning domain knowledge, heuristic strategies, and control strategies. Knowledge about how to learn ranges from general strategies for exploring a new domain to more specific strategies for extending or reconfiguring knowledge in solving problems or carrying out complex tasks. For example, if students want to learn to solve problems better, they need to learn how to relate each step in the example problems worked in textbooks to the principles discussed in the text (Chi, Bassok, Lewis, Reimann, & Glaser, 1989). If students want to write better, they need to learn to analyze others' texts for strengths and weaknesses.

Method

Strategic knowledge is often *tacit knowledge*: experts apply strategies without being consciously aware of exactly what they are doing. Domain knowledge alone provides insufficient clues for many students about how to solve problems and accomplish tasks in a domain. Teaching methods that emphasize apprenticeship are designed to give students the opportunity to observe, engage in, and discover expert strategic knowledge in context.

The six teaching methods associated with cognitive apprenticeship fall roughly into three groups. The first three methods (modeling, coaching, and scaffolding) are the core of traditional apprenticeship. They are designed to help students acquire an integrated set of skills through processes of observation and guided practice. The next two methods (articulation and reflection) are designed to help students focus their observations and gain conscious access and control of their own problem-solving strategies. The final method (exploration) is aimed at encouraging learner autonomy, not only in carrying out expert problem-solving processes, but also in formulating the problems to be solved.

1. *Modeling* involves an expert performing a task so that the students can observe and build a conceptual model of the processes that are required to accomplish it. In cognitive domains, this requires the externalization of usually internal processes and activities. For example, a teacher might model the reading process by reading aloud in one voice, while verbalizing her thought processes in another voice (Collins & Smith, 1982). In mathematics, Schoenfeld (1985) models the process of solving problems by thinking aloud while trying to solve novel problems students bring to class. Recent research suggests that delaying expert modeling of a task until students have tried to generate their own ideas and strategies for performing the task is particularly effective (Kapur, 2008; Schwartz & Martin, 2004).
2. *Coaching* consists of observing students while they carry out tasks and offering hints, challenges, scaffolding, feedback, modeling, reminders, and new tasks aimed at bringing their performance closer to expert performance. Coaching relates to specific problems that arise as the student attempts to accomplish a task. In Palincsar and Brown's (1984) reciprocal teaching of reading, the teacher coaches students while they formulate questions on the text, clarify their difficulties, generate summaries, and make predictions about what will come next.
3. *Scaffolding* refers to the supports the teacher provides to help the student carry out a task (Wood, Bruner, & Ross, 1976). Coaching refers broadly to all the different ways that coaches foster learning, whereas scaffolding refers more narrowly to the supports provided to the learner. These supports can take the form of either suggestions or help, as in Palincsar and Brown's (1984) reciprocal teaching, or they can take the form of

physical supports, as with the cue cards used by Scardamalia, Bereiter, and Steinbach (1984) to facilitate writing, or the short skis used to teach downhill skiing (Burton, Brown, & Fisher, 1984). The timing of the supports is critical. One approach is to provide support at the beginning, and then *fade* the support by gradually removing it until students are on their own. Another approach is to provide the support only after the learner is at an impasse or has failed to perform a task. Research suggests that withholding support up front and providing it only after learners have failed to perform a task is very effective (Kapur, 2012; Schwartz & Martin, 2004; VanLehn, Siler, Murray, Yamauchi, & Baggett, 2003).

4. *Articulation* includes any method of getting students to explicitly state their knowledge, reasoning, or problem-solving processes in a domain. Inquiry teaching (Collins & Stevens, 1983) is a strategy of questioning students to lead them to articulate and refine their understanding. Also, teachers can encourage students to articulate their thoughts as they carry out their problem solving, or have students assume the critic or monitor role in cooperative activities in order to articulate their ideas to other students. For example, an inquiry teacher in reading might question students about why one summary of the text is good but another is poor, in order to get them to formulate an explicit model of a good summary. In mathematics, a teacher may ask for a comparison of incorrect, suboptimal, and correct solutions in order to get students to attend to the critical features of the targeted concept (Kapur & Bielaczyc, 2012).
5. *Reflection* involves enabling students to compare their own problem-solving processes with those of an expert, another student, and ultimately, an internal cognitive model of expertise. Reflection is enhanced by the use of various techniques for "replaying" the performances of both expert and novice for comparison. Some form of "abstracted replay," in which the critical features of expert and student performance are highlighted, is desirable (Collins & Brown, 1988). For reading, writing, or problem solving, methods to encourage reflection might consist of recording students as they think out loud and then replaying the tape for comparison with the thinking of experts and other students.
6. *Exploration* involves guiding students to problem solving on their own. Enabling them to do exploration is critical, if they are to learn how to frame questions or problems that are interesting and that they can solve. Exploration as a method of teaching involves setting general goals for students and then encouraging them to focus on particular subgoals of interest to them, or even to revise the general goals as they come upon something more interesting to pursue. For example, the teacher might send the students to the library to investigate and write about theories as to why the dinosaurs disappeared. In mathematics, a teacher might ask students to design solutions to complex problems that target concepts they have not learned yet. Even though exploration of the problem and

solution spaces might initially lead to incorrect solutions, the teacher can consolidate and build on such an exploration to teach the targeted concepts (Kapur & Rummel, 2012).

Sequencing

Cognitive apprenticeship provides some principles to guide the sequencing of learning activities.

1. *Increasing complexity* refers to sequencing of tasks, such that more of the skills and concepts necessary for expert performance are required (Burton, Brown, & Fisher, 1984; White, 1984). For example, in reading, increasing task complexity might consist of progressing from relatively short texts – with simple syntax and concrete description – to texts in which complexly interrelated ideas and the use of abstractions make interpretation difficult.
2. *Increasing diversity* refers to sequencing of tasks so that a wider variety of strategies or skills is required. As a skill becomes well learned, it becomes increasingly important that tasks requiring a diversity of skills and strategies be introduced, so that the student learns to distinguish the conditions under which they apply. Moreover, as students learn to apply skills to more diverse problems, their strategies acquire a richer net of contextual associations and thus are more readily available for use with unfamiliar or novel problems. For mathematics, task diversity might be attained by intermixing very different types of problems, such as asking students to solve problems that require them to use a combination of algebraic and geometric techniques.
3. *Global before local skills*. In tailoring, apprentices learn to put together a garment from precut pieces before learning to cut out the pieces themselves (Lave, 1988). The chief effect of this sequencing principle is to allow students to build a conceptual map of the task before attending to the details of the terrain (Norman, 1973). Having a clear conceptual model of the overall activity helps learners make sense of the part they are carrying out, thus improving their ability to monitor their progress and develop self-correction skills. In algebra, for example, computers might carry out low-level computations – the local skills – so that students can concentrate on the global structure of the task, and the higher-order reasoning and strategies required to solve a complex, authentic problem.

Sociology

Tailoring apprentices learn their craft not in a special, segregated learning environment, but in a busy tailoring shop. They are surrounded by both masters and other apprentices, all engaged in the target skills at varying levels of expertise. And they are expected to engage in activities that contribute directly to the production of garments, advancing toward independent skilled production. As a result, apprentices learn skills in the context of their application to real-world problems, within a culture focused on expert practice. Furthermore, aspects of the social organization of apprenticeship encourage productive beliefs about the nature of learning and expertise that are significant to learners' motivation, confidence, and most importantly, their orientation toward problems they encounter as they learn. These considerations suggest several characteristics affecting the sociology of learning.

1. *Situated learning.* A critical element in fostering learning is having students carry out tasks and solve problems in an environment that reflects the nature of such tasks in the world (Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991). For example, reading and writing instruction might be situated in the context of students creating a Web site about their town. Dewey created a situated learning environment in his experimental school by having the students design and build a clubhouse (Cuban, 1984), a task that emphasizes arithmetic and planning skills.
2. *Community of practice* refers to the creation of a learning environment in which the participants actively communicate about and engage in the skills involved in expertise (Lave & Wenger, 1991; Wenger, 1998). Such a community leads to a sense of ownership characterized by personal investment and mutual dependency. It cannot be forced, but it can be fostered by common projects and shared experiences. Activities designed to engender a community of practice for reading might engage students in discussing how they interpret difficult texts.
3. *Intrinsic motivation.* Related to the issue of situated learning and the creation of a community of practice is the need to promote intrinsic motivation for learning. Lepper and Greene (1979) discuss the importance of creating learning environments in which students perform tasks because the tasks are intrinsically related to a goal of interest to the students, rather than for some extrinsic reason, like getting a good grade or pleasing the teacher. In reading and writing, for example, intrinsic motivation might be achieved by students communicating with students in another part of the world using electronic mail.
4. *Exploiting cooperation* refers to having students work together in a way that fosters cooperative problem solving. Learning through cooperative problem solving is both a powerful motivator and a powerful mechanism for extending learning resources. In reading, activities to exploit cooperation might involve having students break up into pairs, where one student articulates their thinking process while reading, and the other student questions the first student about different inferences.

Themes in Research on Cognitive Apprenticeship

In the years since cognitive apprenticeship was first introduced, scholars have conducted extensive research toward developing learning environments that embody many of these principles. Several of these principles have been developed further, in particular situated learning, communities of practice, communities of learners, scaffolding, articulation, and reflection.

Situated Learning

Goal-based scenarios (Nowakowski et al., 1994; Schank, Fano, Bell, & Jona, 1994) embody many of the principles of cognitive apprenticeship. They can be set either in computer-based environments or naturalistic environments. Learners are given real-world tasks and the scaffolding they need to carry out such tasks. For example, in one goal-based scenario, learners are asked to advise married couples as to whether their children are likely to have sickle-cell anemia, a genetically linked disease. To advise the couples, learners must find out how different genetic combinations lead to the disease and run tests to determine the parents' genetic makeup. There are scaffolds in the system to support learners, such as various recorded experts who offer advice. Other goal-based scenarios support learners in a wide variety of challenging tasks, such as putting together a news broadcast, solving an environmental problem, or developing a computer reservation system for a hotel. Goal-based scenarios make it possible to embed cognitive skills and knowledge in the kinds of contexts where they are to be used. So people learn not only basic competencies, but also when and how to apply the competencies.

Video and computer technology has enhanced the ability to create simulation environments where students are learning skills in context. A novel use of video technology is the Jasper series developed by the Cognition and Technology Group (1997) at Vanderbilt University to teach middle school mathematics. In a series of 15–20-minute videos, students are put into various problem-solving contexts, such as developing a business plan for a school fair or a rescue plan for a wounded eagle. The problems are quite difficult to solve and reflect the complex problem solving and planning that occurs in real life. Middle school students work in groups for several days to solve each problem. Solving the problems develops a much richer understanding of the underlying mathematical concepts than traditional school mathematics problems.

These kinds of situated learning tasks are different from most school tasks, because school tasks are decontextualized. Imagine learning tennis by being told the rules and practicing the forehand, backhand, and serve without ever playing or seeing a tennis match. If tennis were taught that way, it would be hard to see the point of what you were learning. But in school, students are taught algebra and history without being given any idea of how they might be useful in their lives. That is not how a coach would teach you to play tennis. A coach might first show you how to grip and swing the racket, but very soon you would be hitting the ball and playing games. A good coach would have you go back and forth between playing games and working on particular skills – combining global and situated learning with focused local knowledge. The essential idea in situated learning is to tightly couple a focus on accomplishing tasks with a focus on the underlying competencies needed to carry out the tasks.

Communities of Practice

Lave and Wenger (1991; Wenger, 1998) have written extensively about communities of practice and how learning takes place in these contexts. They introduced the notion of *legitimate peripheral participation* to describe the way that apprentices participate in a community of practice. They described four cases of apprenticeship and emphasized how apprentices' identities derive from becoming part of the community of workers, as they become more central members in the community. They also noted that an apprenticeship relationship can be unproductive for learning, as in the case of the meat cutters they studied, where the apprentices worked in a separate room and were isolated from the working community. Productive apprenticeship depends on opportunities for apprentices to participate legitimately in the community practices that they are learning.

The degree to which people play a central role and are respected by other members of a community determines their sense of identity (Lave & Wenger, 1991). The central roles are those that most directly contribute to the collective activities and knowledge of the community. The motivation to become a more central participant in a community of practice can provide a powerful incentive for learning. Frank Smith (1988) argues that children will learn to read and write if the people they admire read and write. That is, they will want to join the community of literate people and will work hard to become members. Learning to read is part of becoming the kind of person they want to become. Identity is central to deep learning.

Wenger argues that people participate in a variety of communities of practice – at home, at work, at school, and in hobbies. In his view, a community of practice is a group of people participating together to carry out different activities, such as garage bands, ham radio operators, recovering alcoholics, and research scientists. "For individuals, it means that learning is an issue of engaging in and contributing to the practices of their communities. For communities, it means that learning is an issue of refining their practice and ensuring new generations of members. For organizations, it means that learning is an issue of sustaining the interconnected communities of practice through which an organization knows what it knows and thus becomes effective and valuable as an organization" (Wenger, 1998, pp. 7–8).

Communities of Learners

In recent years there has developed a "learning communities" approach to education that builds on Lave and Wenger's (1991) notion of a community of practice. In a learning community, the goal is to advance the collective knowledge of the community, with the belief that this will ultimately support the growth of individual knowledge (Scardamalia & Bereiter, 1994). The defining quality of a learning community is that there is a culture of learning, in which everyone is involved in a collective effort of understanding (Brown & Campione, 1996).

A learning community should ideally have these four characteristics (Bielaczyc & Collins, 1999): (1) diversity of expertise among its members, who are valued for their contributions and given support to develop, (2) a shared objective of continually advancing the collective knowledge and skills, (3) an emphasis on learning how to learn, and (4) mechanisms for sharing what is learned. It is not necessary that each member assimilate everything that the community knows, but each should know who within the community has relevant expertise to address any problem. This marks a departure from the traditional view of schooling, with its emphasis on individual knowledge and performance, and the expectation that students will acquire the same body of knowledge at the same time.

Brown and Campione (1996) have developed a model they call Fostering a Community of Learners (FCL) for grades one through eight. The FCL approach promotes a diversity of interests and talents in order to enrich the knowledge of the classroom community as a whole. The focus of FCL classrooms is on the subject areas of biology and ecology, with central topics such as endangered species and food chains. There is an overall structure of students (1) carrying out research on the central topics in small groups where each student specializes in a particular subtopic area, (2) sharing what they learn with other students in their research group and in other groups, and (3) preparing for and participating in some "consequential task" that requires students to combine their individual learning so that all members in the group come to a deeper understanding of the main topic and subtopics. Teachers orchestrate students' work and support students when they need help.

In the FCL model there are usually three research cycles per year. A cycle begins with a set of shared materials meant to build a common knowledge base. Students then break into research groups that focus on a specific research topic related to the central topic. For example, if the class is studying food chains, then the class may break into five or six research groups that each focus on a specific aspect of food chains, such as photosynthesis, consumers, energy exchange, and so forth. Students research their subtopic as a group and individually, with individuals "majoring" by following their own research agendas within the limits of the subtopic. Students also engage in regular "crosstalk" sessions, where the different groups explain their work to the other groups, ask and answer questions, and refine their understanding. The research activities include reciprocal teaching (Palincsar & Brown, 1984), guided writing and composing, consultation with subject matter experts outside the classroom, and cross-age tutoring. In the final part of the cycle, students from each of the subtopic groups come together to form a "jigsaw" group (Aronson, 1978) in order to share learning on the various subtopics and to work together on some consequential task. Thus, in the jigsaw, all pieces of the puzzle come together to form a complete understanding. The consequential tasks "bring the research cycle to an end, force students to share knowledge across groups, and act as occasions for exhibition and reflection" (Brown & Campione, 1996, p. 303).

A key idea in the learning communities approach is to advance the collective knowledge of the community, and in that way to help individual students learn. The culture of schools often discourages sharing of knowledge by preventing students from working on problems or projects together and from sharing or discussing their ideas. Testing and grading are administered individually, and when taking tests, students are prevented from relying on other resources, such as other students, books, or computers. This traditional approach, often referred to as *instructionism* (see Sawyer, Chapter 1, this volume), is aimed at ensuring that individual students have all the knowledge in their heads that is included in the curriculum. Thus the learning community approach is a radical departure from the instructionist approach that dominates in many schools.

Scaffolding

Scaffolding is a form of support that enables students to tackle complex, difficult tasks that are beyond their ability to engage with independently (Reiser & Tabak, Chapter 3, this volume). Scaffolding can take the form of structured or highly constrained tasks; help systems that give advice when the learner does not know what to do or is confused; guided tours on how to do things; or hints when needed. One common form of scaffolding is to provide an overall structure of a complex task, such that students are guided to individual components of the task at the appropriate moment. The overall structure shows them how each component fits into the overall task. Quintana and colleagues (2004) suggest twenty specific strategies for designing scaffolds to support sense making, inquiry, articulation, and reflection in computer-based learning environments. In most situations, scaffolding naturally *fades* as learners are able to accomplish tasks on their own.

Reiser (2004; Reiser & Tabak, Chapter 3, this volume) points out that most of the work on scaffolding has focused on *structuring* the task for students, in order to make it easier for learners to accomplish the task. But he emphasizes that scaffolding plays another important role – *problematizing* students' performance, or explicitly questioning the key content and strategies used during the task, so that students reflect more on their learning. While this may make the task more difficult, it can facilitate their learning.

The term *scaffolding* was first applied to teaching and learning by Wood, Bruner, and Ross (1976). The term later became associated with Vygotsky's (1978) notion of the *zone of proximal development*, which described how adults can support learners to accomplish tasks that they cannot accomplish on their own. This requires a dynamic determination of what and how learners fail to accomplish a task, and using this information to adapt subsequent instruction and teaching. Hence, the focus of research on scaffolding (see, for example, Davis & Miyake, 2004; Reiser & Tabak, Chapter 3, this volume) has been on supporting individuals in their learning. But Kolodner and colleagues (2003) point out that it is important to scaffold groups as well as individuals. So for example, in their work teaching science, they first provide students with focused collaboration activities to solve simple problems, which they call "launcher units." Engaging in these activities and reflecting on them helps students to collaborate more effectively and to understand the value of collaboration.

In schools, needing to ask for extra help often implies that the student is inferior. Hence, students are reluctant to ask for help for fear of being stigmatized. When scaffolding is provided by computers, it comes without criticism and without others knowing that the student needed help. Computers offer the kind of scaffolding that avoids stigmatization and provides individualized instructional support.

Articulation

In order to abstract learning from particular contexts so that it will transfer to new contexts, it is important to articulate one's thinking and knowledge in terms that are not specific to a particular context (Bransford, Brown, & Cocking, 2000). There have been several very successful examples of how effective group discussions can be as learning environments in classrooms. For example, Lampert (Lampert, Rittenhouse, & Crumbaugh, 1996) showed how fifth grade children can form a community of learners about important mathematical concepts. She engaged students in discussion of their conjectures and interpretations of each other's reasoning. Techniques of this kind have been very successful with even younger children (Cobb & Bauersfeld, 1995) and may partly underlie the success of Japanese mathematical education (Stigler & Hiebert, 1999).

A notable method for fostering articulation in science is the Itakura method developed in Japan (Hatano & Inagaki, 1991). First, students make different predictions about what will happen in a simple experiment, where they are likely to have different expectations. For example, one experiment involves lowering a clay ball on a string into water and predicting what will happen. After students make their initial predictions, they discuss and defend among themselves why they think their predictions are correct. After any revisions in their predictions, the experiment is performed and discussion ensues as to why the result came out the way it did.

Sandoval and Reiser (2004) have developed a computer system called the Biology Guided Inquiry Learning Environment (BGuILE) that supports students in making scientific arguments in the context of population genetics. The system presents the students with a mystery: Why did some of the finches in the Galapagos Islands die during a period of drought while others survived? To solve the mystery, students have to analyze extensive data that were collected by scientists and come up with a reasoned conclusion as to why some finches died while others survived. The Explanation Constructor tool in the system prompts the students to put in all the pieces of a sound genetics-based argument, after they have decided what caused some of the finches to die. Hence, the system scaffolds students to articulate their argument in a much more explicit form than they would normally do.

The Knowledge Forum environment developed by Scardamalia and Bereiter (Chapter 20, this volume; 1994) is an environment where students articulate their ideas in writing and exchange their ideas through a computer network. The model involves students investigating problems in different subject areas over a period of weeks or months. As students work, they enter their ideas and research findings as notes in a knowledge base that is accessible to all computers in the network. The software scaffolds students in constructing their notes through features such as theory-building scaffolds (e.g., "My Theory," "I Need to Understand") or debate scaffolds (e.g., "Evidence For"). Students can read through the knowledge base, adding text, graphics, questions, links to other notes, and comments on each other's work. When someone has commented on another student's work, the system automatically notifies them about it.

The central activity of the community is contributing to the communal knowledge base. Contributions can take the form of (a) *individual notes*, in which students state problems, advance initial theories, summarize what needs to be understood in order to progress on a problem or to improve their theories, provide a drawing or diagram, and so forth, (b) *views*, in which students or teachers create graphical organizations of related notes, (c) *build-ons*, which allow students to connect new notes to existing notes, and (d) *"Rise Above It" notes*, which synthesize notes in the knowledge base. Any of these kinds of contributions can be jointly authored. The goal is to engage students in progressive knowledge building, where they continually develop their understanding through problem identification, research, and community discourse. The emphasis is on progress toward collective goals of understanding, rather than individual learning and performance.

Learning designs that foster *productive failure* (Kapur, 2008) give students opportunities to articulate and externalize their domain knowledge to generate representations and solutions to a novel problem. In the first phase of such a learning design, students struggle to come up with a solution to a problem that is just beyond what they have learned previously – such as writing a formula to characterize the variance of a mathematical distribution or solving an ill-structured problem in kinematics. This *generation phase* provides opportunities for students to explore the benefits and weaknesses of multiple representations and solutions, as well as reason with and refine them in a flexible and adaptive manner. The generation phase is followed by a *consolidation phase* where students are provided with an explanation and solution to the problem (e.g., Kapur, 2012), or an opportunity to discern the deep structure of the problem (e.g., Kapur, 2008). In the consolidation phase, students learn the targeted concept by organizing their student-generated representations and solutions into canonical ones (for a fuller description, see Kapur & Bielaczyc, 2012). Over a series of studies, Kapur and colleagues have demonstrated that productive-failure learning designs give students a level of procedural fluency similar to direct instruction, but result in significantly better conceptual and transfer gains.

Reflection

Reflection encourages learners to look back on their performance in a situation and compare their performance to other performances, such as their own previous performances and those of experts. Reflection has received much attention as a vital aspect of the learning process for both children and adults. Schon (1983) describes how systematic reflection on practice is critical for many professionals engaged in complex activities. Designers of learning environments often build supports for reflection into tasks by asking students to discuss and reflect on the strategies used to guide their actions. Reflection can highlight the critical aspects of a performance and encourage learners to think about what makes for a good performance and how they might improve in the future.

There are two forms that reflection can take, both of which are enhanced by technology: 1) comparison of your performance to that of others, and 2) comparison of your performance to a set of criteria for evaluating performances:

- *Comparison of your performance to that of others:* Because technology makes it possible to record performances, people can look back at how they did a task. One useful form of reflection is an "abstracted replay," where the critical decisions made are replayed (Collins & Brown, 1988). One system that teaches complex problem solving allows learners to compare their decisions in solving a complex problem to those of an expert, so that they can see how they might have done better. This is called *perceptual learning* (Bransford, Franks, Vye, & Sherwood, 1989) because it helps learners perceive what factors are associated with successful problem solving.

- *Comparison of your performance to a set of criteria for evaluating performances:* One of the most effective ways to improve performance is to evaluate how you did with respect to a set of explicitly articulated criteria that are associated with good performance. For example, White and Frederiksen (1998) showed that students who evaluated their performance on projects using a set of eight diverse criteria improved much more than students who carried out the same tasks but did not reflect on their performance in the same way. Furthermore, self-evaluation on the eight criteria helped the weaker students much more than the stronger students.

Effective cognitive apprenticeship asks learners to think about what they are going to do beforehand, try to do what they have planned, and reflect back on how well what they did came out (Gardner, 1991). If learners are presented with criteria to evaluate what they did, this will help them as they plan what they do on the next cycle.

The wide availability of computers and other recording technologies makes performances easier to produce and to reflect on. For example, students can now produce their own news broadcasts, musical performances, or plays, either on audiotape, videotape, or cable television, that go out to other schools or to parents. Furthermore, they can play these back, reflect on them, and edit them until they are polished. One of the best examples of the use of technology for recording performances has been in Arts Propel (Gardner, 1991) with its cycle of performing, reflecting on the performance in terms of a set of criteria, and then performing again.

Conclusion

As these examples illustrate, extensive research over the past 25 years has incorporated the principles of cognitive apprenticeship in the design of learning environments. As computer-based learning environments become more pervasive, there is likely to be continued development of new ways to embody these principles in their design.

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