14. From Cognitive Theory to Instructional Practice: Technology and the Evolution of Anchored Instruction

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Abstract: This chapter discusses evolution of the thinking of the Cognition and Technology Group at Vanderbilt about teaching, learning, assessment, technology, and instructional design under the broad heading of their extended work on the principles and practices of *Anchored Instruction*. It begins by stating a general set of ideas about the characteristics of powerful learning environments and the instructional design principles that are coupled to them. Then in subsequent sections it illustrates how features of the CTGV's evolving work on *Anchored Instruction* helped lead to and embody those principles. The subsequent sections begin by describing the earliest work on *Anchored Instruction*, the development of a set of multimedia instructional materials known as the *Adventures of Jasper Woodbury*. Later sections then describe work that pushed the ideas of *Anchored Instruction* in new and important directions that led to development of the *SMART* model and development of a general inquiry-learning model known as STAR.Legacy. An example of extending the Legacy instructional design model to higher education instructional settings is provided in the context of work in the VaNTH Center on bioengineering and biomedical engineering education. The chapter concludes with thoughts regarding what has been learned over time, challenges that remain in the areas of theory, research and practice, and the role of technology in the larger enterprise of connecting theory, research, and instructional design.

Keywords: Anchored instruction; instructional design; assessment; cognitive theory; technology.

Introduction and Overview

It is not often that individuals have the opportunity to reflect on a body of work that has evolved over a period of almost 20 years with the goal of trying to explicate some of what was learned in the process, as well as discuss what it might mean for theory and research and educational practice. We very much appreciate the opportunity to do so in this volume honoring the many contributions of Norbert Seel to these arenas of intellectual endeavor. The work that we have tried to overview and discuss in this chapter represents the efforts of many individuals who, over a series of years spanning the late 1980s to the early 2000s, were part of the Cognition and Technology Group at Vanderbilt (CTGV)[9]. We were privileged to be members of the CTGV for extended periods of time and work on many of the projects described subsequently in this chapter. However, we make no claim that what we have to say here is representative of the collective voice of CTGV[10].

Perhaps the one thing that the CTGV became recognized for was its *Anchored Instruction* approach to the design of technology-based instructional materials. As explicated in numerous papers and chapters by the CTGV over a more than 15-year period, the collective body of work on *Anchored Instruction* actually reflects an ongoing dialectic among issues of theory, instructional design, research on learning and assessment, technology, teacher knowledge and professional development, and the realities of diverse learners in diverse instructional settings. We cannot do justice to all of what was learned along the way or how it was learned. Rather, in this chapter we attempt to provide a glimpse of part of the evolution of the CTGV's thinking about teaching, learning, assessment, technology, and instructional design under the broad heading of *Anchored Instruction*.

The remainder of the chapter is divided into the following sections. In section two we have tried to state, in a very concise form, a general set of ideas about the characteristics of powerful learning environments and the instructional design principles that are coupled to them. In essence, this knowledge is the product of many years of research and development pursuing the general logic of *Anchored Instruction* and it is derived from related work by many individuals in the fields of cognition and instruction who were not part of the CTGV. We begin at the end so to speak and present some of the broader conclusions so that in subsequent sections it is easier to see how the features of our evolving work helped lead to and embody the current synthetic view. In section three we then describe the earliest and most well known work on *Anchored Instruction*, the development of a set of multimedia instructional materials known as the *Adventures of Jasper Woodbury*.

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[9] There were many participants in the CTGV and a complete list would be prohibitively lengthy. In addition to the present authors, the principals included: Linda Barron, John Bransford, Elizabeth Goldman, Susan Goldman, Ted Hasselbring, Dan Hickey, Cindy Hmelo-Silver, Chuck Kinzer, Xiaodong Lin, Allison Moore, Joyce Moore, Anthony Petrosino, Vicki Risko, Dan Schwartz, Teresa Secules, Diana Sharp, Bob Sherwood, Nancy Vye, Susan Williams, and Linda Zech.

[10] Virtually all the members of the CTGV have left Vanderbilt since 2000. We sometimes refer to the dispersed collective group and the ongoing intellectual community as DCTGV – the Distributed Cognition and Technology Group from Vanderbilt.

Section four then describes work that went beyond the design ideas of the *Jasper* series and pushed the ideas of *Anchored Instruction* in new and important directions that led to development of the *SMART* model. One of the most important directions of the work with the *SMART* model was to generalize the *Jasper* challenge-based and problem–based approach and development of a general inquiry-learning model known as STAR.Legacy. The latter model and its instantiation via technology are described in section five. Then, in section six we describe briefly the process of applying the Legacy instructional design model to higher education instructional settings in the context of the VaNTH Center and its focus on bioengineering and biomedical engineering. In each of the settings where we have pursued elaboration and refinement of ideas about *Anchored Instruction*, technology has played a key role in helping to instantiate our ideas and applications. In section seven we provide some final thoughts regarding what we have learned along the way, what challenges remain in the areas of theory, research and practice, and how we view technology in this larger enterprise.

Characteristics of Powerful Learning Environments and Related Instructional Design Principles

Generalizations and principles derived from a large body of contemporary research and theory on learning, instruction, and assessment (e.g., Bereiter, 1990; Brown & Campione, 1994; Bruer, 1993; Collins, 1996; Scardamalia & Bereiter, 1994), including the collective work of the CTGV on *Anchored Instruction* (e.g., CTGV, 1992a; 1997; 2000), have been presented in a series of major reports from the U.S. National Research Council. These reports include *How People Learn: Brain, Mind, Experience and School* (Bransford et al., 2000), *Knowing What Students Know: The Science and Design of Educational Assessment* (Pellegrino et al., 2001), and *How Students Learn History, Mathematics, and Science in the Classroom* (Donovan & Bransford, 2005). The collective body of scholarly work discussed in these reports has led to the generation of four important dimensions of powerful and effective learning environments. These dimensions can and should influence the principles for designing instructional materials and practices and the use of technologies (see Bransford et al., 2000, CTGV, 2002, Goldman et al., 2005/06, and Pellegrino, 2003, 2004 for more detailed descriptions and elaborations of the ideas that immediately follow, their rationale, and ways in which technology enables their realization). The four dimensions, often referred to as the How People Learn (HPL) framework, include:

Effective learning environments are knowledge-centered. This means that explicit 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. This means that 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 and prior knowledge.

Effective learning environments are assessment-centered. This means that it is especially important 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.

In the sections that follow we attempt to concretize what is meant by the preceding principles by grounding the discussion in *Anchored Instruction* design cases. The presentation includes discussion of which of the above characteristics were included in the work, why, and how. As we noted earlier, the preceding more general ideas about learning environments and instructional design principles were in large part the product of the genesis of research and development elaborating and refining the concepts and practices of *Anchored Instruction*. Our current thinking regarding the design of technology-supported learning environments that reflect the broader design principles derives from over 18 years of cumulative research with students and teachers on ways to motivate and assess exceptional learning (e.g., Barron et al., 1995; CTGV, 1994a,b, 1997, 2000).

The *Adventures of Jasper Woodbury Series*: Genesis of Anchored Instruction

Our initial work focused on the problem of learning with understanding in middle school mathematics, a problem identified in both psychological research and educational practice (e.g., NCTM, 1989). The focus of our efforts was on ways in which cognitive theory and research on problem solving might be connected with mathematics instruction. The result was development of the *Anchored Instruction* approach within which teaching and learning are focused around the solution of complex problems or *anchors*. The initial anchors were video-based stories (originally presented on videodisc) that each ended with a challenge to solve. All of the data needed to solve the challenges are contained in the stories. The problems: (a) are complex (more than 14 steps to solve) and require extended effort to solve (at a minimum, in the range of 3-5 hours for most middle school students); (b) are relatively ill-defined and require significant formulation prior to solving; and (c) have multiple viable solutions. The anchors are designed to engage students in authentic problem solving activities that highlight the relevance of mathematics or science to the world outside the classroom. The design of anchored instruction problem solving environments was a very explicit way to focus on using technology in instructional design to emphasize the knowledge centered and learner centered components of powerful learning environments. In the material that follows we briefly describe one such set of anchored instruction materials and the types of learning they afforded relative to the characteristics of powerful learning environments and principles of instruction discussed earlier.

The cumulative work on *The Adventures of Jasper Woodbury Problem Solving Series* (CTGV 1994a, 1997, 2000) is the single best example of our group's attempt to engage in the process of instructional design based on cognitive theory. Through the process of implementing those designs in multiple classrooms we came to understand the complexities of designing and managing powerful learning environments. For more detailed descriptions of this body of work and data, see CTGV (1992a,b,c, 1993a,b, 1994a; 1997, 2000), Goldman et al. (1997), Lamon et al., (1996), Pellegrino et al. (1991), Secules et al. (1997), Sharp et al. (1995), Vye, et al. (1997, 1998), Williams et al. (1998), and Zech et al. (1994, 1998).

The Jasper series consists of 12 interactive video environments that invite students to solve authentic challenges, each of which requires them to understand and use important concepts in mathematics. The challenges are carefully planned around the knowledge to be learned and how it will be assessed. The learning activities related to the challenge are designed to scaffold learners' knowledge construction by fostering a community of learning and inquiry. For example, in the adventure known as *Rescue at Boone's Meadow* (*RBM*), which focuses on distance-rate-time relationships, a video story begins with Larry teaching Emily to fly an ultralight airplane. During the lessons, he helps Emily learn about the basic principles of flight and the specific details of the ultralight she is flying, such as its speed, fuel consumption, fuel capacity, and how much weight it can carry. Not long after Emily's first solo flight, her friend Jasper goes fishing in a remote area called Boone's Meadow. Hearing a gunshot, he discovers a wounded bald eagle and radios Emily for help in getting the eagle to a veterinarian. Emily consults a map to determine the closest roads to Boone's Meadow, then calls Larry to find out about the weather and see if his ultralight is available. Students are challenged to use all the information in the video to determine the fastest way to rescue the eagle. We developed technology tools to help students navigate the video non linearly as a scaffold to their access of important data embedded in the video story.

After viewing the video, students review the story and discuss the setting, characters, and any unfamiliar concepts and vocabulary introduced in the video. After they have a clear understanding of the problem situation, small groups of students work together to break the problem into sub-goals, scan the video for information, and set up the calculations necessary to solve each part of the problem. Once they have a solution, they compare it with those that other groups generate and try to choose the optimum plan. Like most real-world problems, Jasper problems involve multiple correct solutions. Determining the optimum solution involves weighing factors such as safety and reliability, as well as making the necessary calculations.

The Jasper series focuses on providing opportunities for problem solving and problem finding. It was not intended to replace the entire mathematics curriculum. Frequently, while attempting to solve these complex problems, students discover that they do not have the necessary basic skills. Teachers used these occasions as opportunities to conduct benchmark lessons in which they reviewed the necessary concepts and procedures. Solutions to *RBM* clearly require mathematical knowledge. For example, students have to solve distance-rate-time problems such as how long it would take to fly from point A to point B given the cruising speed of the ultralight. But there are big ideas about mathematics, (e.g., concepts such as rate) that are not necessarily revealed by simply solving problems such as *RBM*. We devised three strategies for helping students abstract important mathematical ideas from their experiences with Jasper adventures. The first was to encourage teachers to use sets of similar Jasper adventures rather than only one, and to help students compare the similarities in solution strategies required to solve them[11]. Gick and Holyoak's (1983) work on abstraction and transfer illustrates advantages of this approach. Often, however, teachers wanted to use dissimilar Jasper adventures (e.g., one involving distance-rate-time, one involving statistics); this reduced the chances of abstraction. We also discovered that additional strategies were needed to help students conceptualize powerful mathematical ideas.

A second strategy for making the use of Jasper Adventures more knowledge centered while also scaffolding student learning was to develop analog and extension problems for each adventure that invited students to solve "what if" problems

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[11] The 12 adventures encompassed four major mathematical content areas, with three adventures for each content area. The three adventures within a content area represented different situations and were progressively more complex.

that changed parameters of the original problems. For example, given the *RBM* adventure discussed above: “What if the ultralight had travelled at a speed of 20 rather than 30 miles per hour? How would that affect the solution?” Or “What if Emily flew to Boone’s Meadow with the help of a 10 mph tailwind and flew back with a 10 mph headwind? Would these two cancel each other out?” (The answer is “no” and it is instructive for students to explore the reason).

Analog problems for *The Big Splash* (*TBS*), a Jasper statistics adventure, further illustrate the importance of promoting what-if thinking. When solving the adventure, students see a particular method used to obtain a random sample and extrapolate the findings to a larger population. Analog problems help students think about alternative randomization procedures that might have been used. Data indicate that the use of analog problems increases the flexibility of students’ transfer. Students benefited greatly from opportunities to develop a more general understanding of sampling and statistical inferencing after solving *TBS* (Schwartz, Goldman, Vye, Barron, Bransford & CTGV, 1998). Similarly, students who solved analog problems after solving *RBM* showed more flexibility in their thinking than students who solved *RBM* without analogs. For example, they were more likely to modify their original solution strategies when presented with transfer problems that could be solved more elegantly with a change in strategy (e.g., CTGV, 1997; Williams, 1994).

A third strategy for helping students understand big ideas in mathematics and scaffolding their learning takes the idea of analog and extension problems one step further. Instead of presenting students with environments that involve only *one-shot* problem solving, we help them conceptualize environments where problems tend to reoccur and it becomes useful to invent ways to deal with these reoccurrences. Theorists such as Lave (1988), Norman (1993), Pea (1993), Rogoff (1990) and others argue that people become smart, in part, by learning to eliminate the need to laboriously compute the answer to important problems that tend to reoccur in their environments. One way to do this is through the invention of “smart” tools. Examples of smart tools that can eliminate cumbersome computations include charts, graphs, computer programs, and gadgets such as watches, speedometers and proportion wheels. We did not want to simply give students tools because these can often be applied without understanding, causing people to fail to adapt when situations change (e.g., see Resnick, 1987). We wanted to help students invent, test, and refine their own smart tools.

We pursued development of smart tools in the context of Jasper Adventures such as *Rescue at Boone’s Meadow* (*RBM*). Instead of receiving a challenge where they are asked to solve a single problem (rescuing the eagle as quickly as possible), students are invited to imagine that Emily becomes an entrepreneur who sets up a pickup and delivery service for people who go camping in her area. She has several different planes to choose from depending on the needs (e.g., some can carry more payload, fly faster, etc.). When customers call to ask for assistance, Emily asks where they are (or where they want to go) and what they want to carry;

she then needs to tell them the trip time and fuel costs as quickly as possible. Different requests involve problems that vary in terms of the location of the destination, windspeed conditions, payload limits that determine which plane must be used, costs due to fuel consumption, and so forth. To calculate the answer to each individual problem is cumbersome, and Emily needs to be as efficient as possible. The challenge for students in the classrooms is to invent smart tools that allow people to solve such problems with efficiency.

In summary, the *Jasper Adventures* provide one example of using cognitive theory and technology to assist in the design of learning environments that demonstrate knowledge-centered and learner-centered features. In developing the problems and then designing instructional strategies and tools to support learning from these materials we tried to adhere to the principles that instruction should be organized around the solution of meaningful problems and that the environment should provide scaffolds for support of meaningful learning. Technology was a significant component in attempts to achieve these objectives.

The *SMART* Model – Extending the Principles of Anchored Instruction

The development, implementation and evaluation of the Jasper materials was coincident with and impacted other related curricular design projects that extended the ideas of anchored instruction. For example, the research and development team subsequently participated in the construction of a second set of curriculum designs, designated by the title *Scientists in Action* (Goldman et al., 1996; Sherwood, Petrosino, Lin, Lamon & CTGV, 1995). In response to student, teacher, and researcher feedback, these curriculum materials underwent development along distinct but somewhat parallel lines to those in the Jasper Adventure series. Once again, designs evolved to incorporate sophisticated forms of scaffolding to enhance effective student learning. Increasingly, the focus was on the two dimensions of a powerful learning environment that many of the Jasper projects had not focused on deeply – formative assessment and community building.

Various methods were explored in the context of working with both the *Scientists In Action* series and the *Jasper Adventures* to provide frequent and appropriate opportunities for formative assessment (Barron et al., 1995, 1998; CTGV, 1994a, 1997, 2000). These included assessment of student-generated products at various points along the way to problem solution such as blueprints or business plans, and assessment facilitated by comparing intermediate solutions with those generated by others around the country who were working on similar problem-based and project-based curricula. In these examples, assessment is both teacher and student generated and it is followed by opportunities to revise the product that has been assessed. The revision process is quite important for students and seems to lead to changes in students' perspectives of the nature of adult work as well as conceptual growth.

We also took advantage of the fact that different ways of organizing classrooms can also have strong effects on the degree to which everyone participates, learns from one another, and makes progress in the cycles of work (e.g., Brown & Campione, 1996; Collins, Hawkins, & Carver, 1991). We have found it beneficial to have students work collaboratively in groups, but to also establish norms of individual accountability. One way to do this is to set up a requirement that each person in a group has to reach a threshold of achievement before moving on to collaborate on a more challenging project, for example, to be able to explain how pollution affects dissolved oxygen and hence life in the river; to create a blueprint that a builder could use to build some structure. Under these conditions, the group works together to help everyone succeed. The revision process is designed to insure that all students ultimately attain a level of understanding and mastery that establishes a precondition for moving from the problem-based to project-based activity.

The larger model we developed became known as *SMART* which stands for *Scientific and Mathematical Arenas for Refining Thinking*. The *SMART* Model incorporated a number of design features to support the four features of an effective learning environment mentioned in the first section of this chapter. For example, a variety of scaffolds and other technology-based learning tools were developed to deepen the possibilities for student learning. They included: (a) Smart Lab – a virtual community for students in which they are exposed to contrasting solutions to problems in the context of being able to assess the adequacy of each; (b) Toolbox – various visual representations that could be used as tools for problem solving; and (c) Kids-on-Line – a tool that featured students making presentations. By using actors who make presentations based on real students work, we were able to introduce presentations with typical, representative errors. This design feature allows students to engage in critical analysis of the arguments and see same age peers explaining their work in sophisticated ways.

As part of this process of providing resources we found that breaking down the isolation of the classroom could also be a powerful way to support learning through social mechanisms. It proved useful to provide students and teachers with access to information about how people outside their classroom have thought about the same problem that they are facing (CTGV, 1994a, 1997, 2000). Such access can help students be more objective about their own view and realize that even with the same information other people may come to different conclusions or solutions. In addition, discussion of these differences of opinion can support the development of shared standards for reasoning. This can have a powerful effect on understanding the need for revising one's ideas and as a motivator for engaging in such a process. Internet and Web-based environments now provide excellent mechanisms to incorporate these processes within the overall *SMART* Model. Some of these mechanisms include interactive Websites with database components which are dynamically updated as students from multiple classrooms respond to items or probes on the Website. We describe an example of this use of the internet and Web below in the context of implementing the *SMART* Model with a *Scientists in Action* adventure.

Reviewing the evolution of one *Scientists in Action* curriculum, the *Stones River Mystery*, will demonstrate the increasing attention paid to embodying all four elements, especially the assessment centered and community centered elements, while further refining the learner and knowledge centered dimensions already present in the Jasper anchored instruction designs. It also illustrates how Web-based resources were introduced into the learning environment.

In the *Stones River Mystery* video, students are presented with the challenge of understanding the complexities of river pollution. In its early form, students engaged in this curriculum watched a video story of a team of high-school students who are working with a hydrologist and a biologist to monitor the quality of the water in Stones River. The team travels in a specially equipped van to various testing sites, and can electronically submit test results to students back at school. The video shows the team collecting and sorting samples of macro-invertebrates from the river's bottom. They also measure dissolved oxygen, temperature, and other water quality indicators. The video anchor poses various challenges to students: first, test and evaluate the water quality at a particular river site to determine if pollution is present, then localize the source of the pollution, and finally, determine the best method to clean up the pollution.

Students use a Web site as they solve each challenge. The site has three components. One component gives individualized feedback to students about their problem solving that they can use to revise their work. For example, when working on the challenge of how to clean up the pollution in Stones River, students access our Web-based version of the Better Business Bureau. This site contained proposals submitted by various companies for how to clean up the pollution in Stones River. Students using the site were asked to select the best company to hire based on the information provided in the proposals and to chose a rationale for their selection. They also indicated their rationale for not selecting each of the other companies. Some of the proposals contained deliberately erroneous scientific information and clean up solutions. Students' selections and rationales were submitted online and they received individualized online feedback (that could be printed out for later reference) about their submissions. The feedback contained information on any problems with their selections and rationales and suggestions for offline resources for learning more about key concepts.

In addition to the formative feedback component, the site had two other components that were designed to draw on the community building potential of the Internet as well as serve a formative assessment function. The site contained a backend database that collected the data submitted by all student users. Information from the database was used to dynamically build graphs that displayed aggregate data on the choices and reasons that students selected. These graphs could be viewed and discussed by the class. Since students' opinions often differ on which company is best and why, the graphs were conversation starters that make this evident and invited discussion about the merits of various choices and about key concepts that support or argue against a specific choice and/or rationale. Students were motivated to take part in discussions about the aggregate data because they understand that it represented the input of students in their class and other participating classes. Finally, the site contained presentations (text plus audio) by actors in which they explain their ideas on which company to hire and why. As mentioned earlier, these presentations purposely contain misconceptions that students often have about the underlying science content. The actors ask students to give them feedback on their thinking (they submit this feedback which is then posted online). In this way, we once again tried to seed the classroom discussion and focus it on understanding important content by bringing the input of the broader learning community into the classroom.

SMART learning environments were designed to foster the development of high standards, rich content, and authentic problem solving environments. But as compared to earlier curriculum units, special attention was paid to assessment and community building. The former category included assessments of student-generated products such as blueprints or business plans, and assessment facilitated by comparing solutions to problems with others around the country who were working on similar problem and project based curricula. In the second category were a number of tools that enabled students to get feedback from a variety of external communities, including parents, community leaders, expert practitioners, and academics. As they evolved, *SMART* learning environments embodied all four instructional design principles discussed earlier: (1) A focus on learning goals that emphasize deep understanding of important subject matter content, (2) The use of scaffolds to support both student and teacher learning, (3) Frequent opportunities for formative self-assessment, revision, and reflection, and (4) Social organizations that promote collaboration and a striving for high standards. Each of these four characteristics was enabled and supported through the use of various technologies for the delivery of resources and the exchange of information. The ability of students and teachers to make progress through the various cycles of work and revision was dependent on the various resource materials and tools that assisted the learning and assessment process. Our research indicated that students who used these tools learned significantly more than students who went through the same instructional sequence for the same amount of time without using the tools (Barron et al., 1995, 1998; Vye et al., 1998).

STAR.Legacy – A Generalized Inquiry Model and Technology Support Tool

The anchored instruction designs described above for areas of mathematics and science – *Jasper Adventures* and *Scientists in Action* – were very much focused on carrying out an extended inquiry process within regular classrooms with reasonable technology capability. They could be executed at varying levels of sophistication depending on access to specific technology infrastructure. In the the course of pursuing these designs, it became apparent that the most effective learning and instruction was transacted in situations where all four elements of powerful learning environments were present. Doing so demands a wide range of resources and tools and also the capacity to organize and manage the instructional and learning process in a way that is faithful to learner exploration and support. One of the things discovered along the way, especially as we implemented *SMART* inquiry environments, was the need for externalization of the overall process. As a result, we developed a software shell for helping people visualize and manage inquiry in a manner that is learner, knowledge, assessment and community centered. Called STAR.Legacy (STAR stands for Software Technology for Action and Reflection), the environment provides a framework for anchored inquiry. Chances to solve important problems, assess one's progress and revise when necessary play a prominent role in the Legacy cycle. The environment can also easily be adapted to fit local needs; in part by having teachers and students leave legacies for future students (hence the name Legacy).

The STAR.Legacy design grew out of collaborations with teachers, students, curriculum designers, educational trainers, and researchers in learning and instruction. One of its virtues is that it makes explicit the different components of an instructional event focused around an inquiry process. Furthermore, it connects the events with learning theory and the four components of powerful learning environments. STAR.Legacy formalizes those components and their rationale within a learning cycle that is easy to understand and follow. Figure 1 shows the home page of STAR.Legacy (Schwartz, Brophy, Lin, & Bransford, 1999; Schwartz, Lin, Brophy & Bransford, 1999). The software features learning cycles anchored around successive challenges that are represented as increasingly high mountains. As learners climb each mountain, they progressively deepen their expertise. Within each challenge students generate ideas, hear perspectives from experts, conduct research and receive opportunities to test their mettle and revise before *going public* with a synthesis of their ideas. The structure of STAR.Legacy is designed to help balance the features of learner, knowledge, assessment and community centeredness.

The home page of STAR.Legacy helps students become more active and reflective learners by being able to see where they are in a research cycle. The importance of this feature became apparent during research that was discussed earlier (Barron et al., 1995; 1998; CTGV, 1994a, 1997; Vye et al., 1998). When working on complex units, students often got lost in the process. In earlier research, we created a visual map of a curriculum unit that was placed in the classrooms; this

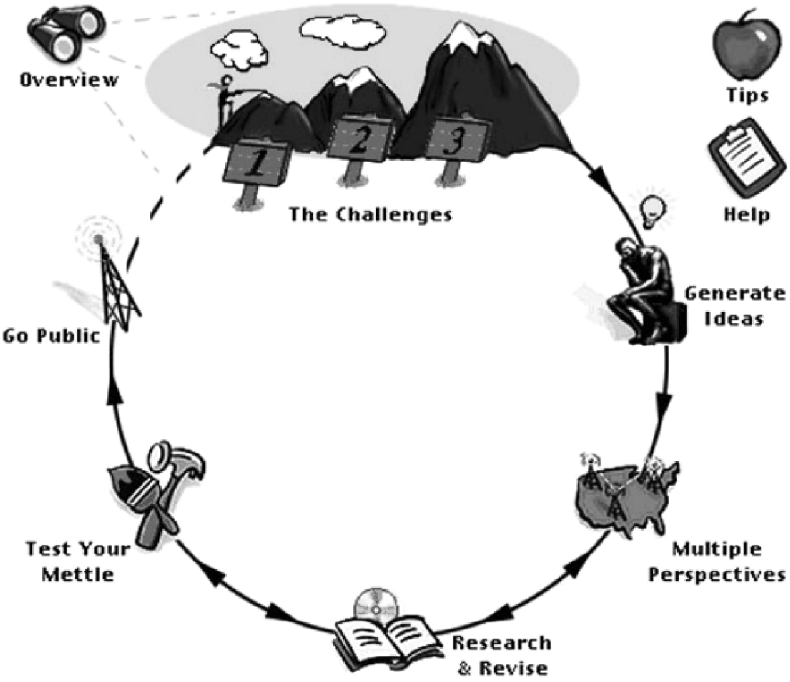

Fig. 1. The STAR.Legacy reference diagram illustrating the organization and sequencing of the components of a multiple challenge inquiry learning cycle.

helped students and teachers understand where they were in the process and where they were going (see Barron et al., 1995 for more information). STAR.Legacy provides a model of inquiry that represents an advance on these earlier designs. It too helps students see where they are and where they are trying to go. White and Fredricksen's (1998) inquiry model for science (which we see as more specific than Legacy but definitely compatible with it) provides an additional illustration of the importance of helping people visualize the processes of inquiry. Teachers can use STAR.Legacy to organize whole class work (by projecting the software on a big screen), or students can work individually or in groups.

The overview section of Legacy (see the top left of Figure 1) allows teachers or students to begin by exploring the purposes of the unit and what they should accomplish by the end. Overviews frequently include pretests that let students assess their initial knowledge about a topic. Teachers can use the pretest to make the students' thinking visible and identify beliefs about the subject matter that may need careful attention (for examples of the value of beginning with students' assumptions, see Hunt & Minstrell, 1994). At the end of the unit students can revisit the pretest and see how much they have learned; the benefits of this are discussed in Schwartz, Brophy, Lin, & Bransford (1999) and Schwartz, Lin, Brophy, & Bransford (1999).

We encourage pretests that are problem-based or design-based rather than simply multiple-choice or true-false tests. The former are more interesting to students initially, and they better reveal students' assumptions about phenomena since their answers are not constrained by pre-determined choices provided on the tests. A pretest for a unit on *rate* may ask students to help a small private flying company design a way to efficiently give people trip time estimates from their airport depending on wind speeds, aircraft speed, and their destination. On a pretest, middle school and even college students usually try to remember formulas and almost never think of inventing smart tools as discussed earlier.

A pretest for one of our units on monitoring rivers for water quality introduces students to Billy Bashinall (a cartoon character) who acts in ways that reveal his assumptions (many are wrong) about water; the students' job is to assess Billy's understanding and prepare to teach him. Students also assess Billy's attitude toward learning (which is quite negative) and discuss their thoughts about how it might be changed. For a more detailed discussion of the idea of using *teachable agents* as part of the instructional design see Brophy, Biswas, Katzlberger, Bransford & Schwartz (1999).

Overall, the *overview* component of Legacy is learner centered in the sense that students are encouraged to state their initial ideas about the overview problem and define learning goals; knowledge centered in the sense that units are designed which focus on important ideas in a discipline; assessment centered in the sense that teachers can gather information about students' beliefs, students can discover that they hold conflicting beliefs as a group, and students can eventually assess their progress when they return to the *overview* problem after completing the unit. The *overview* also supports the development of community centered environments in the sense that teachers can present the pretest as a challenge that all will work on collaboratively (although there can still be individual accountability) in order to communicate their ideas to an outside group (e.g., by *going public* through live presentations or publishing on the Web).

Following the *overview* to a unit, students are introduced to a series of challenges (represented as increasingly high mountains in Figure 1) that are designed to progressively deepen their knowledge. This way of structuring challenges reflects lessons learned about knowledge centered curricula that were discussed earlier. For example, the first challenge for a unit on *rate* in mathematics may ask students to solve the Jasper adventure Rescue at Boone's Meadow, where Emily uses an ultralight to rescue a wounded eagle. It's a calm day, so headwinds and tailwinds do not have to be taken into the account. What is the best way to rescue the eagle and how long will that take? (issues of fuel consumption and capacity come into play in determining this).

The second challenge uses footage of Charles Lindbergh and asks students to decide if he could make it from New York to Paris given particular data such as his fuel capacity and plane speed. Interestingly, Lindbergh couldn't have made the trip without a substantial tail wind. This helps students extend their thinking of rate by considering ground speed versus air speed.

The third challenge invites students to build tools that help them solve entire classes of problems rather than only a single problem. The challenge features Emily's rescue and delivery service. Students are challenged to create a set of "smart" tools that help Emily quickly determine how long it will take to get to various destinations and what the fuel costs will be. Attempts to build tools eventually introduce students to linear and nonlinear functions; for example, changes in wind speeds on different parts of a route introduce students to piecewise linear functions. Examples are provided in Bransford, Zech, Schwartz et al. (1996; 1999).

Within each challenge cycle, Legacy engages students in activities that encourage them to use their existing knowledge, assess their learning, and develop a sense of community with their classmates and the teachers. First, students generate their own ideas about a challenge–either individually, in small groups, or as a whole class. Teachers can listen to students' ideas in whole class sessions and students get a chance to hear the ideas of their classmates. Electronic notebooks in Legacy let teachers capture the thinking of the whole class, or let students who are working in groups capture their thinking and keep it with them as they work through the unit. Teachers can access these notebooks to see how students are approaching the challenges.

After generating their own ideas, students can open *multiple perspectives* and see experts discussing ideas that are relevant to the challenge. An important goal of *multiple perspectives* is to help students (and in some instances teachers) begin to see the relationship between their personal thinking about an issue and the thinking that is characteristic of experts from a scientific community. For example, middle school students may have intuitions that tail winds can help a plane fly faster, but few will have a well-worked out understanding of how to quantify this intuition and how to differentiate air speed and ground speed. In addition, experts can help students understand the value of thinking about the rate of airplane fuel consumption from the perspective of hours of flying time rather than miles per hour.

Opportunities to see *multiple perspectives* have been especially well-received by students. Since they first get to generate their own ideas about a topic (in Generate Ideas), they are able to contrast their own thinking with the thinking of experts. Opportunities to experience contrasting cases are important for helping students develop a deeper understanding of new areas of inquiry (e.g., see Bransford et al., 1989; Bransford & Schwartz, 1999; Schwartz & Bransford, 1998). The fact that Legacy is intended to be an authorable environment also means that teachers can add themselves as one of the multiple perspectives. Having a video of the teacher appear in the media appears to have effects on student attentiveness that go beyond simply having the teacher say the same thing in front of the class.

The "research and revise" component of Legacy provides access to resources for learning, including videos, audio, simulations, and access to the Web. Resources can be different for each of the separate Legacy challenges. For example, a resource for the tools needed for the third Jasper challenge noted above might involve a simple Java-based simulation for building graphs with student-specified scales.

An especially important feature of each Legacy cycle is the *test your mettle* component that focuses attention on assessment, especially self-assessment. For example, students can assess their thinking before *going public* (e.g., by making oral or written presentations or publishing on the Web). For the first Jasper challenge noted above (the Eagle rescue), *test your mettle* might provide students with a checklist to assess whether they have considered important elements such as payload, availability of suitable landing sites, fuel consumption, etc. Alternatively, Legacy might link students to the Jasper Adventureplayer software that allows them to enter their answers to the rescue problem and see a simulation of the results (Crews, Biswas, Goldman & Bransford, 1997).

For the second challenge cycle noted above (the Charles Lindbergh example), *test your mettle* may help students assess their thinking about headwinds and tailwinds (e.g., If Lindbergh takes a test flight where he travels 60 miles to City A with a 10 mph headwind and then flies back with the wind as a tailwind, will the headwind and tailwind cancel each other out?). The Jasper Adventureplayer software (Crews et al., 1997) can also provide feedback on these kinds of variables. The *test your mettle* for the third challenge cycle (the one dealing with smart tools) may provide students with a variety of *call ins* to Emily asking about trip time and expenses to take them to certain locations. Students test their tools to see how efficiently they permit answers to these questions. If the tools need revising (and they usually do), students can go back to *resources*, *multiple perspectives*, or any other part of Legacy. The software is designed to allow flexible back-and-forth navigation–it does not force students into a rigid loop.

At the end of each of the three legacy cycles students have the opportunity to "go public." This includes a variety of options such as making oral presentations in the classroom or posting reports, smart tools, simulations and other artifacts on the Web. The idea of *going public* helps create a sense of community within the classroom because students' and teachers' ideas are being considered by others. For example, in a Legacy used in a college class, students at Vanderbilt went public by publishing essays on the Web that were then reviewed by students from Stanford (Schwartz, Brophy, Lin, & Bransford, 1999). In middle school classrooms, students' essays might be read by other classes or by groups of experts from the community.

At the end of the final challenge in a Legacy unit, students can return to *overview* and revisit the pretest that they took initially. This helps students see how much they have learned in a Legacy unit, and it provides feedback that helps them identify any important concepts that they may have missed.

Most teachers do not have time to create Legacy units from scratch, but we have found that they like to adapt existing units so that they better fit the needs of their classrooms. Teachers may want to choose from several different pretests for a unit, choose from among a number of possible challenge cycles, select a subset of the available resources and *test your mettle*, and so forth. We noted earlier that teachers can also place themselves in the software; for example, as video participants in *multiple perspectives*, *resources*, or *test your mettle*. Over time, Legacy units can be readily adapted to meet teachers' particular goals and needs.

Legacy can also be used to help foster school-wide and community-wide connections by adding videos of local experts who appear in *multiple perspectives*, and resources, and as friendly critics in *test your mettle*. The ability for students within a single class to meet (via video) others from the local school community is powerful. Because students see them visually and learn something about their expertise and interests, our experiences show that they are much more likely to begin conversations and ask questions when they meet these people. We have also observed that students are more likely to go to these people for advice when a project they are working on is relevant to their areas of expertise (Schwartz, Brophy, Lin, & Bransford, 1999; Schwartz, Lin, Brophy & Bransford, 1999).

Legacy is also designed with the idea of having students add their own information to units. The primary mechanism for doing this is to leave a legacy for the next group that explores a unit. Students can add their ideas to *multiple perspectives*, *resources*, or *test your mettle*. For example, students may provide a clip or two in *multiple perspectives* that explains that a challenge initially seemed arbitrary to them and a waste of time but they later realized its value – hence the new students should stick with it. Students might also point toward new resources in the *research and revise* section (e.g., new Web sites) that they found to be particularly valuable. If they wish, students can also add a new *challenge*. Overall, the opportunity to leave a Legacy is very motivating to students and helps them see themselves as part of a community whose goal is to teach others as well as to learn.

Legacy also helps teachers envision a common inquiry cycle that extends across disciplines. Many teachers have found that this helps them communicate with colleagues in other disciplines. A number have used the Legacy cycle to design their curricula even when it is not computerized. The *overview* and *test your mettle* sections of Legacy have been especially important for curriculum development because they focus attention on goals for learning that are more explicit than a mere list of abstract objectives that are often only vaguely defined.

Finally, Legacy also provides a shell for dynamic assessment environments that can be used to assess people's abilities to learn new information. Legacy can capture students' questions, use of resources, tests and revisions. Students who are better prepared for future learning (because of well organized content knowledge as well as attitudes and strategies) should do better in these environments than students who are less prepared (for more discussion see Bransford & Schwartz, 1999).

Anchored Instruction meets Higher Education: Challenge-based Instructional Design in the VaNTH Center

The STAR.Legacy design was intended to be flexible and adaptive to the needs of instructors and learners in a variety of contexts. Evidence of this claim is that it has been employed in both K-12 and adult learning contexts. At the K-12 level it has been used with inquiry-based science learning and with complex mathematics problem solving at the middle school level. With adults it has been used in instructional contexts ranging from electrical engineering (Biswas et al., 1997), educational psychology (Schwartz et al., 1999), and bioengineering education (Harris et al., 2002; Roselli & Brophy, 2006a; Perreault et al., 2006; Martin et al., 2005; 2006), to teacher professional development. For some examples see Schwartz, Brophy, Lin, and Bransford, (1999) and Schwartz, Lin, Brophy, and Bransford, (1999). Across these varied contexts it has proven to be a highly usable design and development environment. It can be as simple or as high tech as one wants and needs. It has the capacity to support complex learning because it links activities to purposes and makes things explicit and manageable. As discussed above, it includes all four components of effective and powerful learning environments. With regard to other technology tools and resources, it can support the use and integration of multiple technology tools and products including multimedia, internet resources, simulations, automated assessments, virtual reality, and communication and dialog systems. Finally, it is highly compatible in its design features with future technology tools and developments in education.

It has proven especially interesting to apply the STAR.Legacy learning cycle in higher education contexts. As we will argue below, it facilitates the enhancement of teaching and learning in higher education contexts that are often very dependent on the traditional lecture and test model of *transferring knowledge*. Such a traditional transmission model of instruction typically supports the development of declarative knowledge and procedures associated with a domain, but does not always provide the experience that learners need to be creative nor does it develop new interest and desire to pursue disciplinary careers. The Legacy cycle provides an alternative approach to designing instruction that supports more advanced learning objectives that develop flexible thinking, sensitivity to multiple perspectives, awareness of professional communities, and greater independence for guiding one's own inquiry. In higher education, learners may often gain these experiences through other activities such as internships, club activities, and other extracurricular professional development experience they have sought out. The Legacy Cycle enhanced with technology provides a mechanism to bring these kinds of experiences into the classroom.

A case in point is the Engineering Research Center (ERC) funded by the U.S. National Science Foundation to enhance bioengineering education by applying advanced theories from the learning sciences and developing accompanying technologies to support learning, instruction and assessment. The Center called, VaNTH, was a collaboration of four institutions including Vanderbilt, Northwestern, Texas (at Austin) and HST (Health, Science and Technology program at Harvard and MIT) (VaNTH 2007). A fundamental conjecture of the VaNTH is that anchored inquiry, specifically challenge-based instruction, is an effective method for achieving the learning outcomes desired for bioengineering students entering a rapidly changing discipline. Further, the lessons learned from the K-12 research presented in the previous sections can apply to undergraduate education of bioengineering. Specifically, the STAR.Legacy Learning Cycle provided a useful framework for organizing learning activities that achieve a balance of the dimensions of the How People Learning (HPL) framework described earlier. Over the past 8 years these frameworks have guided their decisions for what, how and when to teach bioengineering content.

The HPL and Legacy frameworks quickly became a focal point for VaNTH participants to discuss and share ideas about the issues and opportunities for refining their learning environments. Bioengineering domain experts were new to the theories of learning presented by the learning scientists in the Center. However, the explicit description of the Legacy Cycle provided a close analogy to the inquiry cycle engineers use to solve their own problems. Therefore, these frameworks facilitated the communication between experts from the multiple disciplines (domain, learning sciences, assessment and technology) involved in the Center. Now the challenge became bridging these theories into the practice of bioengineering education. Learning Scientists worked with the domain experts to evaluate their current practices and identified opportunities to transform their current practices into enhanced learning opportunities for their students.

For example, biotechnology was a technical elective for seniors in biomedical engineering. One portion of the course revolved around the professor's demonstration of how to design a bioreactor to grow cells in mass quantities. The traditional model of instruction began with the professor's one-minute set up of a context for developing a new process for manufacturing a drug for hemophiliacs with a reduced chance of infection. Subsequent instruction consisted of the instructors modeling of his problem solving process and derivation of mathematical models necessary for sizing a specific type of bioreactor for the application. The context and lectures from this more traditional model of instruction were transformed into a more generative learning environment for the students that engage them in the process of problem solving and modeling experiences. Now, the instruction using the Legacy cycle presented challenges that put students in the role of a bioengineer and presented a grand challenge to transform a market analysis of potential users of a product line into a feasible product line for the company. This set up for their learning experience provides a realistic engineering problem complete with data that needs to be interpreted in order to determine if they have a viable product. In the new instructional model, students began by generating ideas about potential solutions and questions they needed to answer to improve their own comprehension of the grand challenge and the knowledge they needed to better solve the problem. This sets up a series of smaller challenge around factors influencing cell growth, existing methods for growing cells (i.e., the various types of bioreactors) and computational analysis for evaluating the feasibility for a stirred tank bioreactor as one option to the grand challenge (Giorgio & Brophy, 2002; Birol et al., 2002).

The bioreactors challenges organized the learning around the STAR.Legacy cycle beginning with generating ideas around the sub challenges students identified as necessary to solving the grand challenge. They began their inquiry into solving a sub challenge by generating ideas and questions about the challenge and comparing these ideas with perspectives provided by experts familiar with the challenge. Then they conducted their own self-guided research into specific concepts related to these challenge. All of these activities are conducted as a precursor to coming to lecture. Sometimes lectures consisted of the traditional information transfer by the instructor. However, now students were primed to understand the relevance of this knowledge and actively use it to answer their own questions they generated before lecture (Schwartz & Bransford, 1999). For example, in multiple instances students would reference the multiple perspectives that they would want more elaboration on, or clarification of, now that the instructor has provided new knowledge. Therefore, the pre-lecture materials function as a catalyst for formulating questions they want to know more about and the classroom community is established where they are comfortable asking for this additional knowledge. In other situations the instructor would ask students to invent their own mathematical models of the bioreactor systems and the class would discuss the benefits and limits of each of the models. This provides students with valuable feedback on their mathematical competency for representing complex systems. Often the professor would demonstrate his mathematical model of the system. Students would remark that they remember some of the concepts from prior courses, but really did not realize that they applied to these specific situations. However, based on transfer questions after the instructional intervention they demonstrated a better ability to apply these engineering principles. Students would now complete homework assignments with feedback. The final stage in the process was to synthesize everything they learned into a report that articulated a solution to the problem complete with a computational analysis and rational as evidence for the feasibility of their design.

The reformed instructional model of the biotechnology course contained the same content as the traditional instruction and included new activities that required students to process the information in a different way. The learning process was transformed into a knowledge generation activity by students that simultaneously developed their ability to analyze authentic context to identify problems, generate questions to establish personal learning goals, articulate their own mathematical understanding as they apply it to a new problem and synthesize their own ideas to articulate a solution to the problem. This is the *Go Public* phase of the cycle that could end both a written report and an oral report which provides excellent opportunities for students to demonstrate their communication skills and receive feedback on the process.

Multiple examples of bioengineering legacy cycles were critical to the professional development of other faculty in the ERC. The bioengineering instructors quickly comprehended the benefits of the instructional approach of Legacy and the importance of the dimensions of the How People Learn frameworks emphasis on not only the knowledge to be learned, but also on the needs of the learner, methods for providing the feedback and monitor their progress toward course objectives and forming a classroom community. However, the examples from K-12 did not always help them realize practical ways for changing their own practice. Therefore, examples such as the bioreactor challenge became critical to providing a new vision for refining bioengineering classrooms.

VaNTH explored and developed a number of technologies to facilitate instructors' integration of the *How People Learn* instructional design principles and Legacy into their classroom. For example, a classroom communication system involves electronic devices that each student has at their desk that they can use to respond to questions posed during lecture. The results of the students' polls are collected electronically and in seconds a classroom computer can display a histogram of students' responses to the multiple-choice question. This provided the instructor and students with immediate feedback on students' ability to apply their knowledge to conceptual questions (see Roselli & Brophy 2006b). They also developed a courseware authoring and delivery system that managed the presentation of challenges and recorded students' articulation of ideas and questions. The system could also deliver and track students' interactions with simulations and other dynamics and interactive learning during online learning experiences. This system called CAPE (Courseware Authoring and Packaging Environment) provides a highly flexible environment for instructors to present learning activities on the Web to learners outside of class and to record students' ideas and actions during these activities. The instructor can use these records to evaluate students' thinking before students come to class. Now instructors can better anticipate the needs of their students and adjust their lectures and in-class activities appropriately. In addition, the authoring environment contains design patterns of effective learning activities that have been developed over the years. New instructors can use these legacies from prior instructors as building blocks to design their own instruction.

The process of bringing the research from K-12 to higher education leverages similar learning principles. However, the needs of the learners are changing and the infrastructure of the institutions can have an effect on the design. Undergraduates are learning to become more independent learners who possess the potential to flexibly adapt to new situations. They must learn to deal with the ambiguity of dealing with novel situations and develop strategies and attributes for managing the dynamics of these situations. If the classrooms in universities do not provide these opportunities, then breadth of student development as innovative thinkers is delayed until they are on the job. However, the stakes then are higher and the support structures for learning are no longer available. If we are to prepare learners for future learning and increase their potential for noticing innovative opportunities, then our learning environments in higher education must incorporate innovative instructional methods. VaNTH demonstrated the potential for adopting this approach. The Legacy model can increase instructors' comprehension of the guiding learning principles associated with designing effective learning environments.

The process does not need to start from scratch and can build on methods already used in the classroom. It is clear that the *challenge* and *generate ideas* components are key features to drive the learning process, while the other phases can be more flexible depending on the needs of the learners and the available resources. The critical component is that students are engaged in a process of taking action on their current knowledge and reflecting on and refining that knowledge through feedback provided in the learning environment.

Concluding Thoughts and Lessons Learned

It is often noted that technology is really just a tool to support learning and instruction, but it is less often noted or made clear that the nature of the technology tools and their manner of use matters deeply (see for example CTGV, 1996). Our thinking about these issues is the product of over 18 years of work attempting to forge a linkage between learning theory and instructional practice, mediated by advances in technology. As our work evolved over time it became increasingly clear that multiple characteristics of powerful learning environments are needed for maximal payoff. Technology allows for this possibility but also adds levels of complexity. Fortunately, one of technology's affordances is that it is simultaneously capable of supporting the structuring and management of that complexity in ways that also enhance the instructional process. The STAR.Legacy software shell, a technology-based design for inquiry learning, emerged as one example of how to connect learning theory, instructional design and management, and the deployment of multiple technologies.

As the work on *Anchored Instruction* evolved over time, and as technologies became more sophisticated and more powerful, we were able to harness those technologies to instantiate important components of powerful learning environments. We also came to appreciate the fact that there were multiple components that needed to be present and in balance. This was not something we knew at the start and it emerged from multiple attempts to develop materials and practices that were driven by cognitive theory, implement them in real classrooms and instructional settings, study what worked and did not work and why, and then go back and improve the designs. Along the way *Anchored Instruction* got more complicated because what was important was not just the presence of an interesting anchor problem or situation or challenge. Rather, it was the way in which the anchor was used to set up and drive a process of inquiry-based learning that made the difference. So while things got more complicated they also became more straightforward in the sense that the value of a good anchor and what it means to have a good anchor is defined by everything one does with the anchor situation and the affordances it has to support meaningful and deep learning. Not every problem or situation or challenge has these properties and thus it has become an interesting issue to identify with domain experts what are big ideas and important challenges that can anchor a sustained set of instructional activities in a domain.

There are, of course, any number of issues and problems remaining to be solved when it comes to the unpacking of an idea like *Anchored Instruction* and they range from the theoretical to the practical. Also, we would never claim that *Anchored Instruction* is the solution for all instructional and learning situations. That would be a patently absurd claim to make and it would ignore the fact that there are multiple types of knowledge to acquire in a domain and multiple ways in which the learning can and should take place. Nonetheless, if we think in terms of the features of powerful learning environments, we can begin to see where *Anchored Instruction* fits in terms of enabling many critical features of instructional design. What is most interesting to us is that in the process of trying to connect theory, research, practice, and technology, we have gained a deeper sense of the interplay among them and the need to balance academic, aesthetic, and practical needs. Hopefully, in the process the work of the CTGV has provided some food for thought about important principles of cognition and instruction while also providing some useful instructional materials and practices for students and their teachers. This is a collective set of endeavors that we believe Norbert Seel would value highly.

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