5. An Electronics Class That Works: Integrating Science and Technology at the Workbench

During the first semester Mr. Benson’s electronics class divided into singles, pairs, and trios of students who practiced the “basics” of electronics. These basic lessons were organized around individual labs that produced an electronic device, e.g., digital monitor, silent alarm, and audible alarm, etc. Mr. Benson included math and physics lessons in the course of teaching concepts and facts needed to complete labs, and in some cases the labs themselves focused on integrating math, physics, and electronics. Upon completion of this “basics” phase, at the end of the first semester, students moved into an advanced phase involving project work and exploration. Working at an advanced level students made use of their “basic” electronics skills and developed interest in particular technologies to accomplish a wide range of individual and group projects.

The following vignette, based on field notes, is meant to convey a typical day in this classroom:

For twelve students class “begins” at 7:30 a.m. since they routinely start work before the official commencement of the school day. Using the main lab room as a “drop-off” station for backpacks, these boys head instinctively for the adjacent computer lab. Their en masse takeover of the small room places Choa and Jack at the CNC mill. Kent, Jack, and Tom make their home nearby at the robot arm computer, and Mitch soon joins them. The room quickly fills with the noises of chatter, humming computers, and lurching printers. Mr. Benson is quietly working in his little office down the hallway. Just before the bell, he comes out, saying “someone is pretty exuberant.” These ninth grade boys are enjoying themselves, alternatively arguing over strategy and offering hints and encouragement to whoever controls the computer keyboard. Mr. Benson picks up on their excitement as he begins making rounds. Tom pulls out an issue of “Sound Canvas” announcing “they have all this cool stuff. Look how long this keyboard is.” His computer mates marvel with him over the wonderful collection of electronic music components. Just then Kent makes the robot arm move and an impressed Tom asks if he has made a new program. Kent replies that he has modified the original one. Walking out of the computer room, Mr. Benson happily calls over his shoulder to “remember to save” since several of the boys had lost their work in the past few days.

A rambunctious foursome surrounds a corner computer, searching for the Electronic Workbench program. Frank, who was caught with candy just yesterday (for the umpteenth time) joins the group. Outstretched hands jammed with Snickers, he catches sight of Mr. Benson as they pass each other at the doorway. He quickly stuffs the contraband into his pocket. Just then the group lets out a “cheer” at finding the program.
Earnest jockeying for the programmer chair begins, but Frank won’t be moved as he has “something of value” to trade. They soon begin working through an advanced lab on OR gates with Frank in the programmer’s chair and the others happily munching.

When the first period bell rings at 7:40, the twelve earlybirds continue on, oblivious to the fact that the bell is ringing. The day has already started for them. Choa and Jack are having some trouble getting the computer to work, and Mr. Benson suggests they boot it up; the screen soon comes alive with a diagram. No embarrassment here, they plunge forward.

The main lab remains empty, but the open door reveals a brown Z parked just outside the door. Arms and legs of three student installers stick out of the open doors. Benson is satisfied that the car will have a new stereo speaker by week’s end.

Vince, a consummate loner, “messes around a voltmeter” since everyone else has already staked out the computers. He begins to make rounds “à la Mr. Benson,” taking a general interest in whatever problem is occurring at the moment. The computer room remains alive with chatter and progress.

Meanwhile, four boys retire to the main lab room and take up Vince’s abandoned voltmeter. Soon there is a puff of smoke and they all disperse laughing. Mr. Benson’s “radar” sends him toward the general direction of laughter.

Within moments a bell signals first period to close. Several students working on the computer linger. Finally, Mr. Benson chases them out, good naturedly calling to them, “come on, you hackers get out of here!”

Mr. Benson quickly locks the room and heads down to the theater to check on the work of three advanced students who will receive credit for their work on the sound system for an upcoming schoolwide event. Since he is now beginning his preparation period, he takes his time to carefully trace the circuits designed by his students.

**Instructional Goals**

Mr. Benson’s primary purpose was to teach electronics by integrating math, physics, and various forms of technology. His vision of electronics as an “integrated” discipline resulted in a set of instructional goals composed of domain-specific knowledge and skills, complex reasoning skills, work-related attitudes, and cooperative skills. Domain-specific concepts and facts are used as stepping stones for understanding electronics as an integrated domain. Moreover, there is no emphasis on domain skills over generic skills. For Mr. Benson’s purposes both are important. These instructional goals set into motion conditions under which students thought about and practiced electronics at both basic and complex levels.
Problem solving became a primary instructional activity in Mr. Benson’s classroom. During the last month of the class student projects provided many opportunities for enhancing complex reasoning skills. Whereas the “basics” labs offered many opportunities to troubleshoot, the longer projects, which students designed, permitted many opportunities to practice a fuller range of problem-solving skills.

**Analysis of Problem and Generation of Solution Paths.** Mr. Benson typically worked with students to define the problem and then would leave them alone to define their own solution space. Because the technology itself provides students with feedback on their success or failure, Mr. Benson was assured that students would be able to proceed on their own.

**EXAMPLE:** Kent is holding court at the computer surrounded by his fellow computer hackers. He has been fooling around with the electronics workbench software program and having a problem. Mr. Benson troubleshoots aloud and finds the problem. Before leaving Kent to complete the lab he says “you weren’t using NAND theory.” If you would read the manual and see how you put on the generator it will be easier to work with.” This was a very gentle admonishment, almost in a teasing tone, reminding the student that it’s a good idea to pay attention to the concepts and facts discussed in the manual sometimes, rather than just messing around with the software.

**EXAMPLE:** Hasan comes over to where Vince is working, and Vince ignores him, as he is thinking hard about the CNC programming problem. Then he says, “Mr. B., I just figured it out. I have two dots. I made the correction, here. I never had the X coordinate here before.” Mr. Benson muses, “The nice thing about this is that it lets you know you have made a mistake, right?” Vince nods.

**Troubleshooting and Repair.** Students learned repair and troubleshooting skills while working through multiple possible solutions to their problem. (Here “repair” refers to seeking a new problem solution when the current one has failed.) Generally Mr. Benson made rounds, stopping to silently observe work or answer questions. When students appeared stuck he would model troubleshooting (modeling is discussed below), but preferred to leave students on their own or let them use other students as resources:

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1NAND, short for “not AND,” refers to a circuit whose output is the inverse of that produced by an AND circuit.
EXAMPLE: A student working alone has connected his setup but it doesn’t work. Mr. Benson walks through the diagram with the student and compares it to the setup, looks closely at one wire and says, “This may be bad. Let’s change this one here. Let me give you another one.” Mr. Benson goes to the cabinets and chooses a wire, which he gives to the student. The student goes back to his desk and replaces the wire.

EXAMPLE: Kent turns to Mitch and says, “OK, Master, what did I do wrong?” The robot has stopped midmotion, and Kent and Mitch are trying to figure out what had happened. Mitch says, “You send stuff to the robot . . . the robot sends back to you, right?” He and Kent go step by step through the whole sequence of events, trying to find the place where they have incorrectly programmed the robot.

**Deemphasis on Evaluation and Reflection.** We did not often observe particular strategies or efforts made to have students evaluate their circuits or reflect on their project; in fact, Mr. Benson deemphasized these activities. We suggest that there are two possible reasons for this. First, having ready feedback on the success or failure of a solution makes an evaluative emphasis less necessary. When the bulb lights, the alarm sounds, or the robot arm moves, students are signaled to move on. When nothing happens, students step back to perform diagnosis, generation of solutions, and repair. Only if this process fails must they then reflect. Second, in keeping with the “doing” emphasis of vocational education, instead of students entering into reflective postmortems or replays at moments of success they move on to doing a more “real world” project—e.g., installing a car stereo system—or designing a more complex project—e.g., solving circuitry problems via a computer network of four students.

Instances of evaluation and reflection did occur at times. Here a student receives positive feedback from his work but nevertheless seeks a better way to proceed:

EXAMPLE: Mr. Benson and Vince then walk through the logic of the “input” mechanism: the gates and inverters that they’ll need. Mr. Benson draws a circuit on the back of one of their labs. Vince asks Mr. Benson, “Do you have to use two inverters?” Mr. Benson replies, “Now you think about that,” and then continues to talk through the circuit design. Vince asks if that is “the simplest” way to make the circuit. Mr. Benson replies, “That’s your job.” On the next day Vince appears in a rush and slightly excited. He immediately reports to the fieldworker that he has “thought of a new way to do the logic.” He can “do it with two ICS [integrated circuits] instead of three. I asked Mr. Benson if there was a simpler way and he told me to figure it out, and I did.”
Work-Related Attitudes

Mr. Benson keenly focused students on adopting useful attitudes toward their labs and projects. Besides teaching students to apply logic to solving problems, he equally emphasized workplace parameters and responsibility. “Use the tools of the trade” or “take responsibility” were exhortations he used to marshall the students’ cognitive and affective resources in the service of designing and assembling complex circuits. Mr. Benson emphasized a range of work-related attitudes for students.

Responsibility for One’s Actions. During the exploration phase of instruction, students made many decisions as they designed their projects. This exploration required that they invoke skills that would decompose the main goal and make determinations about the purpose of the project, the technology to employ, and how to integrate the technology. If a student does not believe that he is responsible for making these determinations, he will often do the minimal amount of work possible to deal with it. The relatively open assignment to accomplish a project required students to think independently and to make decisions about the material and personal resources required.

EXAMPLE: A group of students discuss their project ideas with Mr. Benson. Hasan has decided to take on a difficult robotics project. Someone volunteered that “Hasan doesn’t know how to program.” Mr. Benson replied, “We’ll find out if he knows it. He will turn in the program, and I will be able to tell what he knows and doesn’t know because it will either work or it won’t.”

Use Personal Interest as a Guide. Mr. Benson did not require that all students learn the same materials; rather, he encouraged students to work on different projects and to “learn to study what they are interested in.” To accomplish this, he waited for them to become interested in one of the simple labs and then suggests that they expand upon this interest using the computer, robot, or digital circuitry. He thought that following personal interest was important for two reasons. First, he thought that each student had individual needs, a belief he frequently expressed with the statement that “life is not a uniform test.” Second, he thought that students would be more motivated to learn if they drew on their individual interests: According to Mr. Benson, students will persist when “their specific learning is relevant to [their] life.” He exhorted students to search for the technology that interests them and to use that technology as the foundation for their projects. The “basics” labs permitted students to practice with many types of technology used in a host of ways, e.g., for design purposes, to engineer a particular product, and as part of an integrated circuit.
EXAMPLE: According to Mr. Benson, Alan came into class at the beginning of the year generally bored with school. Over time he became actively involved with writing up lab results and then doing more and more work. Mr. Benson said that he simply would not let Alan off the hook and he provided him a variety of opportunities. Alan got “turned on” to labs and then eventually became involved with the remote-computer-robot project. Alan was really fascinated with remotes. He had avoided the computer and robot early in the semester. But he saw the computer and robots as helping him explore remotes, so he worked with the guys who were turned on by the robot.

**Focus on Functionality.** Mr. Benson taught the students the importance of achieving the goal of functioning electronic devices. In evaluating student work, Mr. Benson used “functionality, not prettiness” as a criterion. He explained that “A” work requires that students complete all assigned labs, make an “honest” attempt to set up the circuitry, and create a device that functions.

**Cooperative Skills**

Mr. Benson encouraged cooperation among students. It was his belief that students could provide each other with supports for learning difficult material or persisting with a difficult or poorly understood task, and he saw cooperation as a way to have students provide each other with these supports. He preferred to limit group work to pairs to help ensure full participation by each member: “When more than two work together you are likely to get hangers on.” He visited the groups to learn to what degree each student works as a “contributing partner.” Being a contributing partner enforced the work-related attitudes expressed above, that students must learn to be “responsible for their own learning” and that they should use their personal interests as a guide since “life is not a uniform test.”

EXAMPLE: With Alan’s assistance, Stuart assembles the circuit. Stuart moves quickly with Alan’s suggesting alternatives—“no, try that (wire) here” or “move it over one”; Stuart follows Alan’s suggestions sometimes—“Yeah, good move”—but not others—“hey man, don’t mess me up here.” Both are easy and good natured in their interactions: Voices are low, posture relaxed, hands on chins. Bob is looking on, straightening and placing wires at Stuart’s fingertips.

EXAMPLE: Hasan and Tom enter their program into the computer. They explain to the fieldworker that “you have to do this before you work the drill... you can view it before you use the drill.” Jack comes over and watches them: “How far did you make it go down? That’s not right.” Tom answers him, saying, “That’s what
Mr. Benson said . . . OK, turn 250.” Hasan asks him, “How do you know it’s 250?” Tom answers, “I calculated it.”

During the latter months of the class, Mr. Benson suggested that students find new partners if they have a new interest that their old partner does not share.

**Domain-Specific Knowledge and Skills**

**Electronics as an Integrated Discipline.** As mentioned earlier, Mr. Benson thought of electronics as a subject area that integrated several disciplines. He viewed this integrative aspect as providing an advantage for teaching electronics. He spoke of electronics as being a “wonderful discipline because it is not isolated” and gives students the opportunity to see how basic math and mechanics come together. He routinely taught across several domains because “when more math, physics, and the integrated material or electronics is accumulated the potential and possibility for higher learning becomes imaginable.”

Mr. Benson taught math and physics with labs or a particular technology or tool as needed. As an experienced math teacher, he demonstrated a deftness at both the math and its correlation with electronics.

**EXAMPLE:** Mr. Benson distributes the last two sheets that contain problems ranging from simple to complex. The fieldworker recognizes the students will need some algebra, unless they can use some trial and error, including the Pythagorean theorem. Just then Mr. Benson explains to the class that “some students have already had this. Again, not all of you are in algebra; I’ll need to teach this to some of you.” He said he would show them “how to use the Pythagorean theorem in a practical problem-solving way.”

The labs and projects permitted students to correlate what they had learned.

**EXAMPLE:** Vince has the power supply hooked up, but he gets no response from his circuit. He says that he has a problem and suggests a solution: “We need 10V for the speaker, but 5 for the logic. Let’s put in a smaller resistor.” In response to a fieldworker’s query as to why he was reducing resistance, the student explains that “if you have high resistance, you have to use high voltage or low resistance and low voltage.”

In this example the student is integrating his math skills and his electronics knowledge to solve his problem.

**Use Circuitry Logic to Solve “Basic” Electronic Problems.** The “basics” labs provided practice opportunities to learn the logic behind electronics circuitry and
to use this approach to solve simple electronics problems such as using resistors and switches. Mr. Benson selected labs that demonstrated the “logic” of circuits and then used a guided approach to keep students on a purposeful path toward learning particular concepts and facts.

Circuitry logic was learned by students as a way to structure and solve electronics problems; using this logic, they could design circuits or diagnose and repair faulty circuits. In the example below, logic was used to diagnose and solve an electronics problem. Mr. Benson played a logic “game” to help students overcome an impasse.

EXAMPLE: Mr. Benson says, “let’s play an “OR” game. When the gate is closed, both are on so the bulb is . . . what?” (Pause) “On. And when the gate is open, the bulb is also on. That’s why we call it “OR”—it’s an either/or situation. What can change this?” Stuart answers, “Add an inverter,” pointing to the lower input position. Mr. Benson says, “What does this change?” Stuart is silent, screwing up his face. Alan provides the correct answer: “The same thing will happen.”

Students were also encouraged to develop “truth tables” to reflect the logic of alternative gate combinations that can be employed in the design of circuits. These tables provided a tool for analyzing the circuit logic:

EXAMPLE: Mr. Benson works through a lab on “OR” gates and asks, “What can change this? Think about your truth tables.” Stuart answers, “Add a second inverter,” pointing to the output position. Continuing to sketch, Mr. Benson says, “Let’s check it out. If you close the top [input] you have ‘low’ and on the bottom [input] you have ‘low,’ so the output is . . .?” The three boys answer “low” in unison. Mr. Benson continues: “If you open the doors on top, you have . . . .” He is silent, permitting the boys time to answer. Then he continues again: “And if closed on the bottom you have ‘high’ and the bulb turns ‘on.’ If you have a high on the bottom and a gate open on top, you will have a ‘high’ above and the bulb still turns ‘on.’” They all answer correctly.

Mr. Benson used basic domain knowledge (circuitry logic) as a means to transition students into complex reasoning about electronics.

**Technical Knowledge.** Students are expected to explore technology and to practice with specific electronic components in order to learn about electronics. Over the years, according to Mr. Benson, he has discovered that “technical ideas” such as digital circuitry and robotic engineering are difficult to teach and learn unless they are placed in the context of concrete, hands-on experimentation and investigation. In support of this approach, Mr. Benson provides the students
with access to a wide range of technology, including computer hardware and software, robotics, pneumatics, and digital remotes.

Classroom Design

Mr. Benson’s classroom design grew not only out of his goals but also out of his expectations about students and how they learn, the school placement and curriculum policy, and his beliefs about teaching.

Over the years Mr. Benson had learned to design his classes based on the “chemistry of the classroom” created by the mix of students enrolled. He advocates flexibility in the schedule and class structure to manage “classroom chemistry,” which may change from year to year and even month to month. In designing the electronics classroom, he incorporated a fair degree of autonomy in order to combat student boredom while he taught theory and electronic “basics.”

By contrast, Mr. Benson said he is unable to incorporate the same degree of flexibility into the math class that he teaches because the program is “restrictive,” i.e., students must master a certain body of knowledge to advance to the next class. In industrial arts he teaches the same students over several semesters and is not accountable to cover a standard set of concepts and skills before passing them on to other instructors.

Teacher Roles

Mr. Benson primarily took on the role of “master” to student “apprentices.” He provided students whatever assistance they needed early on, but as they gained skills, he reduced this interaction with them or modified his role as closer to an equal, to acknowledge their increasing expertise. Moreover, he demonstrated his “love” and appreciation for electronics. He was enthusiastic about the work at hand, and even tolerated mild chiding for this from a few students, who would later acknowledge that “the infectiousness” of his manner contributed to their own interest in electronics.

Although he was openly friendly to students, he did not encourage students to question his authority as teacher. However, he did not pretend to be an unquestionable authority on electronics: As a teacher his watchword was to “expect to be asked things you know nothing about.” He had learned that a teacher knows “about half of what kids can think up.”

In keeping with the master-apprentice relationship, Mr. Benson adapted to his students’ interests and their abilities. He set different standards for students,
depending on their level of skill and knowledge. For example, he would encourage an advanced student’s attempts to use the electronics software to understand underlying concepts. For another student who had difficulty simply working with computers, he urged the student to try an experiment with the computerized robot. Working with the robot was a prized opportunity for most of the class, and the student was motivated to learn enough about computer operations to use the robot.

Because he worked with each student based on their needs and interest, Mr. Benson naturally individualized evaluation. He believed that individual student evaluation required that the teacher become involved with student projects because “if you don’t do these things you will be unsure about achievement in your classroom.”

Situated Learning

Mr. Benson situated the learning of electronics—together with correlated physics and mathematics lessons—in a variety of tasks. During the first half of the semester most learning was situated in electronics “labs” that taught basic “building block” domain skills and knowledge: introductory vocabulary, facts, concepts, and technical skills. After the basics were in place, Mr. Benson situated the learning in more complex tasks that made use of students’ basic knowledge (e.g., about current flow, diodes, and series and parallel resistors) and skills: Such a task would be to assemble and test a digital monitor. Advanced projects took 1–3 weeks to complete, and students worked in groups and individually. Projects included advanced work on the robot using the computer and remotes; using advanced electronic workbench software to further examine basic lab experiments; designing and building the sound system for use at school events; and designing and building electronic locks.

Mr. Benson expected that the “sharper” students would use the basic concepts and physical models to design representations using the computer or the robot as a tool. For example, one group became interested in counting mechanisms and built an adapter connected to a number of component systems. They employed a variety of arrangements for the component systems and the counting adapter. Another group, interested in the computer programs, linked four computers together to form a network and work simultaneously on the same program. They then used the network to explore and test gates. Finally they did group simulations of their original experiments. This process turned out to be a very effective way for students to identify new insights from their original experiments.
Although Mr. Benson carefully sequenced the instructional plan, he did not expect students to march through it in lock step. As mentioned above, he believed that students should be encouraged to learn in the ways that most interest them. He allowed students to learn even the basics using whatever appealed most to them, e.g., the labs, robot, or computer.

He also thought that sequenced instruction should be alternated with periods of exploratory learning. He used an architectural analogy to describe this teaching strategy:

“I build on the first and second floors and then I stop and stay on the second floor for awhile. This is when kids explore, get excited, and really work together . . . bounce off each other. They might even get involved with peripheral things . . . like air cylinder valves. This is also when I have to teach some algebra and physics. Then I move to building the third or fourth floors and again I stop and stay on the fourth so that kids can explore again.”

Using only sequenced instruction was an approach that he associated with novice instructors “who [are] forever involved with building blocks” and do not permit students time to integrate those blocks of knowledge.

Exploration took up the last portion of the semester, which in fact was entirely unplanned. Mr. Benson did not assign a particular project or task, nor establish a project plan. Instead, he challenged students, bringing together students with similar interests, and maintained the expectation that students explore more technically difficult projects. He said that students learned that “simple experiments teach a lot and that when they [the experiments] are brought together more complex systems are possible.” This approach required a student to take the time to develop and integrate the “building blocks” in the first part of the semester.

**Culture of Practice**

Mr. Benson’s desire to involve students in authentic practice activities required that he find ways to mesh the “culture of expert practice” with the “culture of schooling.” He apparently intuits the usefulness of “expert practice” for carrying out his goals to teach a broad mix of skills and to create an experimental and workplace ethic in the classroom. He acknowledges that his approach is uncommon in schools because “there is a cost to inquiry. You have to set up

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2Although “culture of expert practice” is the term usually used for this approach to classroom design, “culture of adult electronics hobbyist” would better describe the reference culture that Mr. Benson modeled his classroom on.
broad conditions and make them work.” He believes that situating learning in authentic practice helps build confidence in students: “I try to build in a problem, by having broad conditions, so kids will have something to deal with and they will develop a belief in their own abilities.” He bases the design and conduct of his class on his own experience as practitioner and learner: “I don’t know why I do what I do. I don’t hesitate though because this is what I know should be done. I know it because I make furniture. I design circuits. I play with the robot. I fool around with room drawings and houses.”

During the first semester of the class student work was not organized in ways that reflected expert practice. Rather, students worked in coacting pairs and depended heavily on the teacher’s assistance. Beginning students, then, were not fully autonomous but would look to Mr. Benson and a partner for help. The coacting teams imply a more teacher-centered classroom, where the teacher directs activities and students respond.

As students learned more concepts and facts and could discuss the logic of basic circuits, they entered the “expert” culture. As part of authentic activities, students not only became engaged in more advanced ideas and projects, but were expected to organize their own “self-managing” groups for accomplishing the project. Responsibility, freedom, and independent discretion was encouraged. The norms for “self-management” reflect a classroom where the teacher guides students as they independently work on projects.

The classroom norms promoted exploration and a high level of learning. Students were expected to search for a group of 2–3 other students with similar interests. Students were not required to worry about appropriate roles within a group but were expected to cooperate sufficiently to accomplish the project. Moreover, because students would be experimenting with new ideas, Mr. Benson emphasized that students strive for functionality over perfect design:

EXAMPLE: After introducing students to computerized numerical control software and explaining its use in manufacturing, Mr. Benson noted that “we’re not striving for that accuracy, but to appreciate that accuracy.”

EXAMPLE: Mr. Benson made a general announcement to the kids: “If you program only five lines, it’s okay. If you got the essence of what you are supposed to have in it, that is the point. Now, if you can design a program that would allow this arm to run smoothly,  

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3 Sociotechnical systems theory coins useful terms for worker arrangements in the workplace. A coacting team works together, but on individually defined tasks, and reports to a supervisor. Teams with fewer managerial controls over their work are labeled “self-managing.” For additional reading in this area, see Hackman and Oldham, 1980.
instead of herky-jerky, that would be good. I saw a couple of robots last week that were the smoothest thing.”

The culture of practice reflected Mr. Benson’s best efforts to blend the electronics design and engineering world with the classroom. Since his “workers” were students with little knowledge when they entered the course, he accommodated their novice status by providing a practice-rich learning opportunity that did not necessarily simulate actual work in an electronics laboratory. Rather, the culture was more like that of the hobbyist or amateur motivated to enjoy, apply, and increase his or her expertise.

**Motivation**

It was Mr. Benson’s experience that the majority of students in his class hailed from the ranks of the general track of students and tended not to be motivated by lectures on theory or lock-step progression through the subject. Mr. Benson took responsibility for motivating students and used classroom design for that purpose. Although he recognized that his students did not come into the course motivated to work hard or to learn at a high level, he did not accept the inevitability of low-level learning or passing out “easy As.” Instead, he looked for a way to make learning more appealing.

He thought that his best chance was to keep them engaged with interesting technology and to avoid rules whenever possible. He believed that autonomy would appeal to his students. For example, he permitted student groups to determine their own pace on experiments, by assigning all twenty labs at the beginning of the semester. He requested that students generate about half using the computer software and the other half using actual physical components and testing units, but as the semester evolved and it became evident that some students were “really drawn” to one approach or the other, he permitted individuals to complete a majority of the projects using the one that interested them—say, the computer or the robot. He was demanding—“get it done”—but flexible—“in your own time and according to your interests.”

Mr. Benson believed that students were best motivated by being prepared and supported to do a task, and he employed all aspects of classroom design to provide this source of motivation. He organized the learning tasks so “basic” skills would be used for more advanced projects. He was willing to accept a certain amount of “bad behavior,” but not bad performance.

Additionally, Mr. Benson enhanced motivation through his enthusiasm for teaching “an integrated domain” and by providing students with advanced
technology and equipment (his entrepreneurial skill in acquiring these classroom resources is described below). From his understanding about learning and teaching, Mr. Benson sees the teaching of complex subjects and teacher excitement as a way to ignite motivation in the classroom:

“I love the challenge of interfacing materials. This stems from a concept no longer taught in teacher education—transfer of knowledge. Teachers are not taught the emotional side of learning—that kids need to have the emotional preparation to learn on any given day. Transfer of knowledge [may also] come from things beside the teacher . . . the materials, beautifully designed equipment . . . this helps to program the transfer of knowledge, because kids are ready to learn.”

Students discussed Mr. Benson’s “infectious” enthusiasm as similar to that of a “kid in a candy store.” One student’s explanation for Mr. Benson’s interest in students and teaching electronics is that he “basically loves it.”

Mr. Benson believed in the importance of support in the sense of the “emotional connection” between teacher and student. He explained his philosophy of this “emotional connection” in these terms: “Don’t throw kids back; take action so they don’t fail,” and “let’s make this kid a better person by challenging and supporting, not by handholding.”

Mr. Benson graded on the basis of individual effort. He did not distribute grades on a curve. He did not challenge students to compete against one another but rather urged that they strive to improve their own performance.

**Cooperation**

Mr. Benson encouraged students to work as contributing partners on their lab assignments and advanced projects. In advanced projects, he permitted students to find new work partners if their original lab partner had different interests. Mr. Benson actively urged students to move on to new ideas and new partners because he wanted students to benefit from the knowledge resources and persistence on the task that group work encourages. In keeping with his hands-off approach during the exploratory phase, he did not form groups, but occasionally suggested that students with similar interests talk together about a group project. His simple guide was that friends tend to work well together and that people who “goldbrick get dropped,” i.e., lazy students can’t find partners.
Teaching Techniques

Mr. Benson employed a variety of teaching techniques to support his instructional goals and classroom design. He made use of brief lectures primarily to discuss the purpose and importance of a particular circuit or application and to present facts. As with many vocational education classrooms, many days passed without lectures. The reason for this is straightforward: The primary focus of the class was on “thinking while doing” electronics. Thus, much of Mr. Benson’s time was spent circulating through the rooms of the class, observing and providing one-on-one instruction opportunistically. Below we describe some specific teaching techniques.

Articulation

Articulation methods were integral to Mr. Benson’s instructional style. He used questions to help students verbalize their difficulties in problem solving and to help them make links between previous lessons and their current problem:

EXAMPLE: Mr. Benson walks over to two boys working together. One seated on a stool, the other lying across the table. Mr. Benson doesn’t seem to mind. He gets his pen and draws a diagram right on the table. He talks about the diagram as he draws, then begins to ask questions. “Where should you put the inverter?” Student points correctly. Mr. Benson says, “Okay. Let’s try that and see what happens. Suppose the doors open. Will this turn on the alarm?” Student says no. Mr. Benson says, “therefore, the inverter won’t solve my problem. Let’s put it here and see what happens.” Student says, “so we need to use two inverters.” Mr. Benson answers, “That’s right.”

EXAMPLE: Mr. Benson and Curt walked into the computer room. Mr. Benson says, “So far you have spent a lot of time on that same lab. I wonder why that is.” Curt made a diagram of what he had been doing in the lab, showing Mr. Benson where the problems were for him. Mr. Benson watched, saying, “Yes . . . yes.” Then the two of them went off into the other room together.

Modeling

Mr. Benson effectively modeled “logic” and “problem solving” for students. This was an especially effective way for students to observe how “experts” solved electronic problems. In the example below he models how to program the CNC milling machine:
EXAMPLE: Tom was working on a program, and brought it to Mr. Benson. “I found out how to get here . . . how do I get over here?” Mr. Benson questions and talks through the answer: “What is this? Change in X, change in Y . . . what is this radius here? Okay, from here you have to subtract.” Tom pulled out a calculator and began subtracting. “Okay, 619 . . . okay, that’s it. You go with that.” “Do these numbers sound right, Mr. Benson?” Mr. Benson replies, “I don’t know,” as Tom filled in the lines of the program on the sheet. Mr. Benson says, “Okay, the distance from the starting point to there is what?” Tom answers “X is .95.” Mr. Benson continues walking through the reasoning: “You defined this distance, right here? Isn’t this .75? Only if this arc comes across. You know what this is . . . .58.” Tom volunteered, “That gives you four.” Mr. Benson says, “We know this point right here . . . .75. Okay, so we know this distance . . . you have to make a translation from this point to this point . . . You need to know this. What is this distance, from here to here? .158.” Tom objected, saying, “We aren’t even dealing with this. We go from here, to here.” Mr. Benson corrects him, saying, “No, remember this point . . . the radius comes here. It is perpendicular. You did the calculation to find this distance. It is whatever this distance is here, from the radius.” Tom figured it, and said, “So, .908.” Mr. Benson replies, “That sounds familiar.” Tom asked him if it was right; he replied, “I think so. That gives you 1750.”

In modeling problem solving, Mr. Benson also models perseverance and ingenuity. During the exploration periods of his class, his students sometimes come across problems that he does not immediately know how to solve. In such cases, he admits, his first inclination is to delay an answer, but he forces himself to work through the problem with the students: “Sometimes I come up with the wrong answer initially, but eventually I figure out how to solve the problem. I don’t mind when the kids see me stumble, because that is a good lesson about the real world—if you know the basics and you are willing to explore, you can figure most anything out.”

Scaffolding and Fading

When students reached an impasse during the “basics” labs, he played the “logic game” as a scaffold until students could articulate the logic of the electronics circuit on their own.

EXAMPLE: Ali and Curt are working on a lab on OR gates and are having difficulty. Mr. Benson provides instruction: “Okay, now on the backside of the chip . . . how many LED segments light when pin 1 is connected to the ground?” The boys mumble in response, “One.” Mr. Benson continues, “What are the applications of this? Why would you want to use this?” The boys answer, “Digital
clocks, microwaves.” “Right . . . counters of some sort . . . things that count up, and count down. Okay, which pin has to be connected to ground to light up?” Ali and Curt offer incorrect answers. Mr. Benson then asks, “How many LEDs are going on?” Curt answers correctly, “Five.” Mr. Benson finally asks, “Okay, which pins do you use to light up?” The boys point. Mr. Benson goes on, “You want to create all the numbers from zero to nine . . . list all the pins you use to make A through F.” Unsatisfied with Ali and Curt’s working knowledge of OR gates, Mr. Benson examines the boys’ lab writeup, and says, “Listen to my words . . . I’m going to eat a lollipop, or a cupcake.” The boys reply, “One OR the other.” Mr. Benson asks them, “Can I have a lollipop AND a cupcake? If I have both of them, I’m smiling. What happens if I don’t have either?” Ali answers, “Not smile.” Mr. Benson nods, saying, “Look at this . . . the outcome is smiling. If you have a lollipop, do you smile?” The boys nod and say “yes.” He goes on, “if you have a cupcake, do you smile?” They nod. “Now look at this thing. . . . What does the truth table say?” he asks them. The boys look at it awhile, and Curt says, “It’s backwards,” somewhat tentatively. Mr. Benson [fading now] says to them, “Go back, and check to see what you did. See if you read it correctly.” He moves on to the next table.

During the later exploratory phases of the class, when activities are less teacher directed and students organize their own “self-managing” groups, he “fades” by reducing his assistance. Students are expected to use each other as resources and to draw on knowledge and skills learned in the basics phase of the class to assist their own project success.

**Coaching**

Mr. Benson used coaching to hint to students how to apply their knowledge to the problem at hand. This was an important technique for him because the majority of instruction occurred one-to-one with students rather than in lectures. In the course of these individual and small group instruction efforts, he would often suggest that students attempt alternative paths to solving a problem, moving either toward greater complexity or diversity. He persisted with this technique even when students voiced irritation that he was not explicitly answering their questions:

EXAMPLE: Lorenzo and Vince report to Mr. Benson that they are trying to make the SCR (silicon controlled rectifier) keep the alarm on, but it is not working. Mr. Benson engages them in a series of questions about the alarm circuit. Vince shows Mr. Benson the pieces of the circuit that they have already built. Mr. Benson suggests how to divide up the task, but the pieces have already both been built, apparently by Vince. They next walk through the
logic of the “input” mechanism: the gates and inverters required. Mr. Benson suggests that Vince find a simpler way to accomplish the circuit. After Mr. Benson leaves, Vince complains that Mr. Benson didn’t answer his original question about the SCR. However the following day, Vince simplifies the alarm circuit, thereby solving the problem. The SCR now functions.

Mr. Benson also coached in the motivational sense of the word, exhorting students to persevere (“keep trying, son”) and praising success. Perhaps the strongest coaching message he communicated occurred during walking rounds when he would pause several minutes to observe some students who had overcome a faulty design problem or successfully debugged a circuit—the feedback for students was his ready grin and a wink of approval.

Exploiting “Real World” References

Although Mr. Benson had not worked as an electronics engineer, he was familiar with the applications of electronics in industry and everyday uses in homes. He offered these references during lectures to reinforce the relevancy of classroom lessons to the real world. At other times he would discuss an application or industrial use of a circuit when students became “stuck” during a logic game. These more concrete examples seemed to assist students to think more globally about a concept or application, helped them solve the circuit before them, and energized their efforts.

EXAMPLE: A group of students is having difficulty understanding the logic behind OR gates. He “plays the logic game” and then explains that “this is how to use three gates to do the same thing. That’s the role of the engineer. To figure out ways to monitor and keep track of things under different conditions. Finish your experiment and complete the truth tables. Okay?” He walks away, returning later to look at the circuit and truth tables. Satisfied with the results, he energetically declares, “Now you can be masters of burglary . . . but listen sons, I don’t want you to go out there and try this stuff, so let’s hook up a siren to this.” Stuart says seriously, “A police siren, sir?” Mr. Benson grins and continues. “Think about it. You can use transistors to trigger—like what you did last semester.” Alan says, “Remember the sound generating . . . .” Mr. Benson cuts in, “Right. Take one and build it in. It’s processing system, input, output (he recites the order of the circuit). You can use a 550 time circuit, or use an LED if you want.” Mr. Benson’s suggestions go beyond what is asked in the experiment.
Student Perceptions and Accomplishments

The students had diverse goals for attending the electronics class. While a few had specific learning goals and/or work interests related to the class, many thought it would be an easy class (especially the junior varsity football players who made up one clique in the class). Others had no personal goals but were simply placed there by the counselor. After the first semester of class, however, students reached a near consensus on their expectations for the class. They knew that they could do well if they made a personal effort, because individual attention was available from a knowledgeable and fair teacher. The mix of instructional goals, classroom design, and teaching techniques coalesced, such that students reached a common understanding of the classroom and their roles in it. In short, they became engaged and “enculturated” (Collins et al., 1989).

Students also achieved a variety of specific accomplishments in the practice of electronics. We discuss each below.

Electronics Knowledge and Skills

Students produced electronic devices that integrated various forms of technology. Because their learning was situated rather than decontextualized, they learned increasingly complex knowledge and application through the practice of authentic electronics activities. Some students focused on hands-on learning throughout the class; these wanted always to build a more complex device, adding an additional component to produce a new function. Others focused on more abstract representations. These students used the computer to design electronic devices and then explored extensions or alternatives by manipulating the computer representation.

Over the school year, students became facile with the technical language associated with electronics. Mr. Benson marveled at their gains in this area: “I’m totally amazed to see kids go from having to learn simple electronic terms in the fall to building logic devices and using the proper language at the close of the school year.”

Skills became meaningful for students because students perceived and understood their use. When surveyed, over three-quarters of students indicated that the class taught them to “use electronics.” The opportunities to practice and build applications in class reinforced this relationship for students:

EXAMPLE: Mitch offers that “logic” and “math” are useful skills that can be applied. Asked to further discuss “applied math,” Mitch responds that people “use math” in commonplace, everyday
reasoning situations. He links the “logic” entailed in electronic circuitry problems to other “math” [reasoning skills] required for everyday problem solving. Vince agrees with Mitch’s description of this application from electronics class.

**Cooperative Skills**

Students learned that not all groups or group members are equal and that certain behaviors are less helpful than others in contributing to group goals. In focus groups, students voiced divided opinions on the value of group work. One opinion holds that students who do not participate because of lack of knowledge or unwillingness will hold back the group because they engage in nonproductive activities (“messing around”) that distract other group members. The other view accepts that because the material is difficult, students find that a working partnership, where information and effort are shared, can help the group. This second view is similar to that discussed by Collins et al. (1989) where they stress the benefits of group work: Group synergism, better task understanding, confrontation of ineffective strategies, and development of collaborative work skills.

Students elaborate further:

Vince: “Some groups are not working well. They are messing around. ‘Participation is the key for a group to work well’ [quoting a principle Mr. Benson had enunciated many times].” This comment seemed to refer to Curt’s work group. Several others in the group looked at Curt when Vince volunteered this. Curt reacted slightly by shifting in his chair; but, he said nothing in response. Alan added, “We share information in the group. We know different stuff and this makes the group work well.” But then he offered a reservation on how group work constrains individual exploration: “The groups can’t let you investigate the finer points (of electronics).” Stuart counters that group work can make it easier for some individuals to participate in electronics: “It [electronics] is difficult. This is the first time I’ve ever had electronics.” Alan supports Stuart’s contention that electronics is a difficult subject for some, implying that for such persons group work is especially valuable: “People have different levels of knowledge. It is harder for some.”

These comments indicate that students recognize the concept of distributed knowledge: Different people can bring different knowledge and skills to a task for the good of the whole group.

Some students took on the role of “helper” rather than contribute to solving problems. Unfortunately, these students lost opportunities to learn more
complex ideas or technologies. Often they did not fulfill their helper role, requiring that the more engaged partner intercede. From Mr. Benson’s view, these students “could” take a more responsible role, but refrained. He simply required that each student maintain some involvement with the project, but generally the partners were left to contend with whatever effort each determined to put forth:

EXAMPLE: When the lecture is over, Lorenzo takes off to get some materials. He returns and struggles to get the first piece of wire cut and stripped. He is looking pretty pathetic. Vince gets up and walks to the supply and tools closet, returns with another pair of wire cutters and says “This might work better” and gives the newer cutters to Lorenzo. Vince continues to explain his circuit logic to the fieldworker. Lorenzo continues to struggle. Vince reaches out to Lorenzo, who hands him the wire cutters and wire. Lorenzo goes off to get more wire. Vince quickly cuts and strips five pieces of wire, each about four inches long. Lorenzo returns with more wire. Vince announces, “Now we need a power supply to see if it works.” Lorenzo goes off to look for a power supply in the cabinet and returns empty handed. Vince has finished his wiring idea and is frustrated by this news. Vince then tries to negotiate with the students at the next table to borrow their power supply. He strikes a deal whereby his group can use it until the table three group needs it, then table three gets it back. As Vince is plugging it in he says: “Lorenzo, next time if you’re the first one in, get a power supply.”

As Vince and Lorenzo’s interaction demonstrates, the more engaged students often helped take responsibility for instructing and motivating the less engaged members of their groups.

While the focus group discussion revealed complaints about individual group members, survey results indicated a generally positive evaluation of cooperation. Most (80 percent) said that “working in groups is a good way to learn,” and the class “helped (me) learn to work with others” (66 percent agree).

**School Context**

*Access to Knowledge*

Mr. Benson’s classroom design and his instructional goals required that he have both simple and sophisticated materials and equipment available. His constant press to improve the level of instruction convinced the district to invest in equipment for his labs. He was able to obtain equipment (e.g., computers and a robot arm) through a district-financed lease/purchase arrangement with local businesses. Additionally, he invested personal funds (one to two thousand
dollars) to purchase materials that he could not lease. Moreover, the students themselves in the course of their learning were able to develop materials to support further learning: For example, during the first semester students built breadboards for the electronics labs. Students even helped fund projects with their own money at the beginning of the year.

**Press for Achievement**

The electronics class was an elective class and attracted a mixed group of students who were interested in the subject area. Mr. Benson was viewed as a “no nonsense” teacher who expected students to work. Students who chose the class with a different expectation dropped it early on. Mr. Benson enjoyed the “mix” of students and was pleased when several of his “low-motivation” students became strongly engaged during the second semester, developed a “love” for technology and electronics, and decided to return for a second year.

Mr. Benson had high expectations for student achievement, which he believed was linked to effort and the freedom to explore. He worked with and supported any student who would try. Students came to understand this. During focus group discussions, students explained that they worked hard, not to please Mr. Benson, but because of their own personal interest and desire to achieve.

**Professional Teaching Conditions**

Mr. Benson found administrative support for his industrial arts classes, but for different reasons from those of Mr. Price. Mr. Benson had crafted a high-level vocational program that had high enrollments and attracted a heterogeneous group of students. His classes were a prime example of “good” vocational education in a comprehensive high school.

Mr. Benson was much more of an “insider” than other teachers we observed. He spent much of his free time in the teacher lounge socializing with other teachers. He received the “Teacher of the Year” award from the local chamber of commerce during this last school year. The district sought his assistance in planning for integrating academic and vocational education efforts, and he arranged for speakers to provide inservice training to the entire teaching staff about integration. Despite his many efforts to advance vocational education in the school, the school’s strong college preparation focus made it difficult to generate sufficient enrollment to offer separate sessions for both beginning and continuing electronics students.