STUDENT-CENTERED LEARNING

ACTIVE LEARNING and COMPILATION OF BEST TEACHING PRACTICES

COMPiled by

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Student Centered Learning:

• Elevates the teacher from the focal point to a guide & coach.
• The Goal involves engaging students in learning that will require Problem-Solving
Many college teachers today want to move past passive learning to active learning, to find better ways of engaging students in the learning process. But many teachers feel a need for help in imagining what to do, in or out of class, that would constitute a meaningful set of active learning activities.

The model below offers a way of conceptualizing the learning process in a way that may assist teachers in identifying meaningful forms of active learning.

**A Model of Active Learning**

![Diagram of active learning model]

**Explanation of the Components**

This model suggests that all learning activities involve some kind of experience or some kind of dialogue. The two main kinds of dialogue are "Dialogue with Self" and "Dialogue with Others." The two main kinds of experience are "Observing" and "Doing."

**Dialogue with Self:**

This is what happens when a learner thinks reflectively about a topic, i.e., they ask themselves what they think or should be thinking, what they feel about the topic, etc. This is "thinking about my own thinking," but it addresses a broader array of questions than just cognitive concerns. A teacher can ask students, on a small scale, to keep a journal for a course, or, on a larger scale, to develop a learning portfolio. In either case, students could write about what they are learning, how they are learning, what role this knowledge or learning plays in their own life, how this makes them feel, etc.

**Dialogue with Others:**

This can and does come in many forms. In traditional teaching, when students read a textbook or listen to a lecture, they are "listening to" another person (teacher, book author). This can perhaps be viewed as "partial dialogue" but it is limited because there is no back-and-forth exchange. A much more dynamic and active form of dialogue occurs when a teacher creates an intense small group discussion on a topic. Sometimes teachers can also find creative ways to involve students in dialogue situations with people other than students (e.g., practitioners, experts), either in class or outside of class. Whoever the dialogue is with, it might be done live, in writing, or by email.
Observing:
This occurs whenever a learner watches or listens to someone else "Doing" something that is related to what they are learning about. This might be such things as observing one's teacher do something (e.g., "This is how I critique a novel."); listening to other professionals perform (e.g., musicians), or observing the phenomena being studied (natural, social, or cultural). The act of observing may be "direct" or "vicarious." A direct observation means the learner is observing the real action, directly; a vicarious observation is observing a simulation of the real action. For example, a direct observation of poverty might be for the learner to actually go to where low income people are living and working, and spend some time observing life there. A vicarious or indirect observation of the same topic might be to watch a movie involving poor people or to read stories written by or about them.

Doing:
This refers to any learning activity where the learner actually does something: design a reservoir dam (engineering), conduct a high school band (music education), design and/or conduct an experiment (natural and social sciences), critique an argument or piece of writing (the humanities), investigate local historical resources (history), make an oral presentation (communication), etc.

Again, "Doing" may be direct or vicarious. Case studies, role-playing and simulation activities offer ways of vicariously engaging students in the "Doing" process. To take one example mentioned above, if one is trying to learn how to conduct a high school band, direct "Doing" would be to actually go to a high school and direct the students there. A vicarious "Doing" for the same purpose would be to simulate this by having the student conduct a band composed of fellow college students who were acting like (i.e., role playing) high school students. Or, in business courses, doing case studies is, in essence, a simulation of the decision making process that many courses are aimed at teaching.

Implementing This Model of Active Learning

So, what can a teacher who wants to use this model to incorporate more active learning into his/her teaching do? I would recommend the following three suggestions, each of which involves a more advanced use of active learning.

1. **Expand the Kinds of Learning Experiences You Create.**

   The most traditional teaching consists of little more than having students read a text and listen to a lecture, a very limited and limiting form of Dialogue with Others. Consider using more dynamic forms of Dialogue with Others and the other three modes of learning. For example:

   - Create small groups of students and have them make a decision or answer a focused question periodically,
   - Find ways for students to engage in authentic dialogue with people other than fellow classmates who know something about the subject (on the web, by email, or live),
   - Have students keep a journal or build a "learning portfolio" about their own thoughts, learning, feelings, etc.,
   - Find ways of helping students observe (directly or vicariously) the subject or action they are trying to learn, and/or
   - Find ways to allow students to actually do (directly, or vicariously with case studies, simulation or role play) that which they need to learn to do.
2. **Take Advantage of the "Power of Interaction."**

Each of the four modes of learning has its own value, and just using more of them should add variety and thereby be more interesting for the learner. However, when properly connected, the various learning activities can have an impact that is more than additive or cumulative; they can be **interactive** and thereby multiply the educational impact.

For example, if students write their own thoughts on a topic (Dialogue with Self) **before** they engage in small group discussion, (Dialogue with Others) the group discussion should be richer and more engaging. If they can do both of these and then observe the phenomena or action (Observation), the observation should be richer and again more engaging. Then, if this is followed by having the students engage in the action itself (Doing), they will have a better sense of what they need to do and what they need to learn during doing. Finally if, after Doing, the learners process this experience by writing about it (Dialogue with Self) and/or discussing it with others (Dialogue with others), this will add further insight. Such a sequence of learning activities will give the teacher and learners the advantage of the Power of Interaction.

Alternatively, advocates of Problem-Based Learning would suggest that a teacher start with "Doing" by posing a real problem for students to work on, and then having students consult with each other (Dialogue with Others) on how best to proceed in order to find a solution to the problem. The learners will likely use a variety of learning options, including Dialogue with Self and Observing.

3. **Create a Dialectic Between Experience and Dialogue.**

One refinement of the Interaction Principle described above is simply to create a dialectic between the two principle components of this Model of Active Learning: Experience and Dialogue. New experiences (whether of Doing or Observing) have the potential to give learners a new perspective on what is true (beliefs) and/or what is good (values) in the world. Dialogue (whether with Self or with Others) has the potential to help learners construct the many possible meanings of experience and the insights that come from them. A teacher who can creatively set up a dialectic of learning activities in which students move back and forth between having rich new experiences and engaging in deep, meaningful dialogue, can maximize the likelihood that the learners will experience significant and meaningful learning.
NAVIGATING THE BUMPY ROAD TO STUDENT-CENTERED INSTRUCTION

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INTRODUCTION

In the traditional approach to higher education, the burden of communicating course material resides primarily with the instructor. In student-centered instruction (SCI), some of this burden is shifted to the students. SCI is a broad approach that includes such techniques as substituting active learning experiences for lectures, holding students responsible for material that has not been explicitly discussed in class, assigning open-ended problems and problems requiring critical or creative thinking that cannot be solved by following text examples, involving students in simulations and role-plays, assigning a variety of unconventional writing exercises, and using self-paced and/or cooperative (team-based) learning. In traditional instruction, the teacher's primary functions are lecturing, designing assignments and tests, and grading; in SCI, the teacher still has these functions but also provides students with opportunities to learn independently and from one another and coaches them in the skills they need to do so effectively. In recent decades, the education literature has described a wide variety of student-centered instructional methods and offered countless demonstrations that properly implemented SCI leads to increased motivation to learn, greater retention of knowledge, deeper understanding, and more positive attitudes toward the subject being taught (Bonwell and Eisen 1991; Johnson Johnson and Smith 1991a,b; McKeachie 1986; Meyers and Jones 1993).

We use student-centered instruction extensively in our courses and discuss it in teaching workshops we present to faculty members and graduate teaching assistants. The workshop participants generally fall into two categories. On the one hand are the skeptics, who come up with all sorts of creative reasons why student-centered methods could not possibly work. On the other hand are the converts, who are sold on SCI and can't wait to try it. We know the fears teachers have about the instructional methods we advocate, having had most of them ourselves, and we can usually satisfy most of the skeptics that some of the problems they anticipate will not occur and the others are solvable. We worry more about the enthusiasts who leave the workshop ready to plunge right in, imagining that the spectacular results promised by the literature will show up immediately.

The enthusiasts may be in for a rude shock. It's not that SCI doesn't work when done correctly—it does, as both the literature and our personal experience in two strikingly different disciplines richly attest. The problem is that while the promised benefits are real, they are neither immediate nor automatic. The students, whose teachers have been telling them everything they needed to know from the first grade on, don't necessarily appreciate having this support suddenly withdrawn. Some students view the approach as a threat or as some kind of game, and a few may become sullen or hostile when they find they have no choice about playing. When confronted with a need to take more responsibility for their own learning, they may grouse that they are paying tuition—or their parents are paying taxes—to be taught, not to teach themselves. Good lecturers may feel awkward when they start using student-centered methods and their course-end ratings may initially drop. It's tempting for instructors to give up in the face of all that, and many unfortunately do.

Giving up is a mistake. SCI may impose steep learning curves on both instructors and students, and the initial instructor awkwardness and student hostility are both common and natural. The key for the
instructors is to understand how the process works, take some precautionary steps to smooth out the bumps, and wait out the inevitable setbacks until the payoffs start emerging.

TRADITIONAL STUDENTS IN A NONTRADITIONAL CLASS: A PAINFUL ODYSSEY

Woods (1994) observes that students forced to take major responsibility for their own learning go through some or all of the steps psychologists associate with trauma and grief:

1. **Shock:** "I don't believe it-we have to do homework in groups and she isn't going to lecture on the chapter before the problems are due?"

2. **Denial:** "She can't be serious about this-if I ignore it, it will go away."

3. **Strong emotion:** "I can't do it-I'd better drop the course and take it next semester" or "She can't do this to me-I'm going to complain to the department head!"

4. **Resistance and withdrawal:** "I'm not going to play her dumb games-I don't care if she fails me."

5. **Surrender and acceptance:** "OK, I think it's stupid but I'm stuck with it and I might as well give it a shot."

6. **Struggle and exploration:** "Everybody else seems to be getting this-maybe I need to try harder or do things differently to get it to work for me."

7. **Return of confidence:** "Hey, I may be able to pull this off after all-I think it's starting to work."

8. **Integration and success:** "YES! This stuff is all right-I don't understand why I had so much trouble with it before."

Just as some people have an easier time than others in getting through the grieving process, some students may immediately take to whichever SCI method you're using and short-circuit many of the eight steps, while others may have difficulty getting past the negativity of Steps 3 and 4. The point is to remember that the resistance you encounter from some students is a natural part of their journey from dependence to intellectual autonomy (see Kloss 1994). If you provide sufficient structure and guidance along the way, by the end of the course most of them will reach satisfactory levels of both performance and acceptance of responsibility for their own learning.

In the remainder of this paper, we list common faculty concerns about student-centered instructional methods and offer responses. Much of the discussion involves issues associated with cooperative learning, the method that in our experience occasions the most vehement student resistance.

FACULTY CONCERNS

If I spend time in class on active learning exercises, I'll never get through the syllabus.

You don't have to spend that much time on in-class work to have a significant impact with it. Simply ask questions occasionally and give the students a short time to come up with solutions and answers, working either individually or in small groups. Then collect answers from several randomly selected individuals or groups. One or two such exercises that take a total of 5-10 minutes can keep a class relatively attentive for an entire period.

On a broader note, much of what happens in most classes is a waste of everyone's time. It is neither teaching nor learning. It is stenography. Instructors recite their course notes and transcribe them onto the board, the students do their best to transcribe as much as they can into their notebooks, and the information flowing from one set of notes to the other does not pass through anyone's brain. A more productive approach is to put substantial portions of the course notes-lengthy prose, detailed derivations, complex diagrams-in handouts or coursepaks, leaving gaps to be filled in and sprinkling questions and instructions like "Prove," "Justify," "Verify," "Explain" throughout the presentation. Spend class time only on the most critically important and conceptually difficult parts of the notes, leaving the students to cover the rest for themselves. The many hours of class time you will save by doing this should be more than sufficient for all the active learning exercises you might want to use. Your classes will be more lively and effective, you will still cover the syllabus, and you might even be able to augment it to include topics you never had time to cover before. Moreover, if you announce that some of the gaps and exercises in the
handouts will be the subject of test questions and then keep your promise, the students will even read the handouts—at least after the first test.

If I don't lecture I'll lose control of the class.

That's one way to look at it. Another is that several times during a class period your students may become heavily involved in working on or arguing about what you're trying to get them to learn, and it may take a few seconds (never longer once you get the hang of it) to bring their attention back to you. There are worse problems!

I assign readings but many of my students don't read them and those who do seem unable to understand the material independently.

In our experience, the only reliable way to compel most students to read the assigned material is to test them on it without covering all of it in class. Some instructors use short quizzes at the beginning of every period for this purpose; others who don't want to spend that much class time giving and grading quizzes prefer to include questions on the readings in their regularly scheduled examinations. In either case, the instructors soon learn that testing students on material not explicitly covered in class inevitably leads to vigorous protests. There are several ways to ease the students' transition from reliance on the instructor to self-reliance. Create graphic organizers that visually illustrate the structures and key points of the readings (Bellanca 1990) and later ask the students to do so. Prepare study guides that summarize critical questions answered by the readings and then include some of the questions on the exams. Give brief or extended writing assignments that call on the students to explain portions of the readings in their own words. Well-constructed writing assignments compel students to process material actively, identifying important points or connecting the material to their prior knowledge (Brent and Felder 1992).

Some of my students just don't seem to get what I'm asking them to do—they keep trying to find "the right answer" to open-ended problems, they still don't have a clue about what a critical question is, and the problems they make up are consistently trivial.

An essential feature of any skill development program is practice and feedback. Most students have never been taught to solve open-ended problems or think critically or formulate problems, so that the first time you assign such an exercise they will probably do it poorly. Collect their products and provide constructive comments. In addition, reproduce several products (perhaps slipping in one of your own as well), hand them out without attribution, go over some of them in class to illustrate the sort of thing you're looking for, and suggest ways to make good products even better. Modeling of this type helps students understand the process they need to go through to improve their own work. After several similar assignments and feedback sessions, students will start giving you the kind of results you're looking for and they will also begin giving one another meaningful feedback in group work. This approach serves a double purpose: the students gain more skill and confidence and you gain a classroom of teaching assistants who can help each other learn. By the end of the course some of them may be performing at a surprisingly high level.

When I tried active learning in one of my classes, many of the students hated it. Some refused to cooperate and made their hostility to the approach and to me very clear.

Instructors who set out to try student-centered instruction in a class for the first time are often unpleasantly surprised by the fierce negativity of some responses. Many who don't anticipate such reactions get discouraged when they encounter them, give up, and go back to more comfortable but less effective methods.

To minimize resistance to any student-centered method, try to persuade the students from the outset that you are neither playing a game nor performing an experiment, but teaching in a way known to help students learn more and understand better. You can reinforce your point about the effectiveness of SCI by offering variations on one or more of the following observations:

You've all had the experience of sitting through a good lecture, believing that you understood it, and then later when you tried to do the homework you realized that you didn't get it at all. By putting you to work in class I'm giving you a jump start on understanding the material and doing the homework efficiently.
Unless you're a Zen monk, you can't sit still and keep your mind focused on one thing for more than a few minutes. In lectures your attention drifts, first for short intervals, then for longer ones, and by the end of a straight 50-minute lecture you're probably getting less than 20% of what's being said. Doing something active from time to time during the lecture substantially increases the amount of information you actually get. It also cuts way down on boredom.

When you go out to work, I guarantee you'll be working in teams. When companies fill out surveys asking them what skills they want their new employees to have, teamwork skills are usually ranked either first or second. Since working in teams is what you're going to be doing on your job, you may as well start learning how to do it now.

(To students complaining about being slowed down by having to explain material they understand to slower teammates.) If you ask any professor, "When did you really learn thermodynamics (or structural analysis or medieval history)?" the answer will almost always be "When I had to teach it." Suppose you're trying to explain something and your partner doesn't get it. You may try to put it in another way, and then think of an example, then another one. After a few minutes of this your partner may still not get it, but you sure will.

In our experience, most students bright enough to complain about being held back by their classmates are also bright enough to recognize the truth of the last argument.

I'm having a particularly hard time getting my students to work in teams. Many of them resent having to do it and a couple of them protested to my department head about it.

Cooperative learning tends to be the hardest student-centered method to sell initially, especially to high academic achievers and strong introverts. The points given above about the prevalence of teamwork on most jobs, the importance of teamwork skills to most employers, and the fact that we learn best what we teach, can help. Perhaps the most effective selling point for cooperative learning (unfortunately) involves grades. Many research studies have demonstrated that students who learn cooperatively get higher grades than students who try to learn the same material individually (Johnson et al. 1991b). Before assigning group work for the first time, we may mention a study (Tschumi 1991) in which an instructor taught an introductory computer science course three times, once with the students working individually and twice using group work, with common examinations in the first two classes. In the first class, only 36% of the students earned grades of C or better, while in the classes taught cooperatively, 58% and 65% of the students did so. Those earning A's in the course included 6.4% (first offering) and 11.5% (second offering) of those who worked cooperatively and only 3% of those who worked individually. There was some student resentment about group work in the first cooperative offering and almost none in the second one, presumably because the instructor was more skilled in the method the second time and possibly because the students in the second cooperative class knew about the results from the first class.

Persuading students that group work is in their interest is only the first step in making this instructional approach work effectively. The instructor must also structure group exercises to promote positive interdependence among team members, assure individual accountability for all work done, facilitate development of teamwork skills, and provide for periodic self-assessment of group functioning. Techniques for achieving these goals are suggested by Johnson et al. (1991a), Felder and Brent (1994), and many other books and articles in the recent education literature. Instructors new to cooperative learning are advised to have several such references handy when planning activities and assignments and dealing with problems.

If I assign homework, presentation, or projects to groups, some students will "hitchhike," getting credit for work in which they did not actively participate.

This is always a danger, although students determined to get a free ride will usually find a way whether the assignments are done individually or in groups. In fact, cooperative learning that includes provisions to assure individual accountability—such as individual tests on the material in the group assignments—cuts down on hitchhiking (Johnson et al. 1991a,b). Students who don't actually participate in the homework will generally fail the tests, especially if the assignments are challenging (as they always should be if they are assigned to groups) and the tests truly reflect the skills involved in the assignments. If the group work only
counts for a small fraction of the overall course grade (say, 10-20%), hitchhikers can get high marks on the homework and still fail the course.

One way to detect and discourage hitchhiking is to have team members individually or collectively distribute the total points for an assignment among themselves in proportion to the effort each one put in. Students want to be nice to one another and so may agree to put names on assignments of teammates who barely participated, but they are less likely to credit them with high levels of participation. Another technique is to call randomly on individual team members to present sections of project reports or partial solutions to problems, with everyone in the group getting a grade based on the selected student's response. The best students will then make it their business to see that their teammates all understand the complete solutions, and they will also be less inclined to put a hitchhiker's name on the written product and risk having him or her be the designated presenter.

Many of the cooperative teams in my class are not working well-their assignments are superficial and incomplete and some team members keep complaining to me about others not participating.

The interpersonal challenges of cooperative learning may be severe. Students have widely varying intellectual abilities, work ethics, and levels of sensitivity to criticism, and a substantial part of the cooperative learning experience is learning how to confront and work through the conflicts that inevitably arise from these variations.

One way to get groups off to a good start is to have them formulate and write out a set of team standards and expectations, sign it, make copies for themselves, and turn in the original to you. As the course proceeds, have them periodically evaluate how well they are working as a team to meet those standards and what they might do to work more effectively. You may invite teams with serious problems to have a session in your office. If they do, try to help them find their own solutions rather than telling them what they should do.

Taking a few minutes in class to focus on critical teamwork skills can make a major difference in how groups function. Periodically select an important activity like brainstorming or resolving conflicts and offer tips in class on effective ways to carry out the activity. An effective technique is to present a short scenario describing a common problem and brainstorm solutions with the class.

You may also give teams the last resort option of firing uncooperative members after giving them at least two warnings, and you may give individuals carrying most of the workload the option of joining another group after giving their uncooperative teammates at least two warnings. In our experience, teams almost invariably find ways of working things out themselves before these options have to be exercised.

Teams working together on quantitative problem assignments may always rely on one or two members to get the problem solutions started. The others may then have difficulties on individual tests, when they must begin the solutions themselves.

This is a legitimate concern. An effective way to minimize it is for each team member to set up and outline each problem solution individually, and then for the team to work together to obtain the complete solutions. If the students are instructed in this strategy and are periodically reminded of it, most of them will discover its importance and effectiveness and adopt it. There is also merit in assigning some individual homework problems to give the students practice in the problem-solving mode they will encounter on the tests.

I teach a class containing students in minority populations that tend to be at risk academically. Does active, cooperative learning work in this kind of setting?

In fact, the most frequently cited cooperative learning success story comes from the minority education literature. Beginning in the mid-1970's, Uri Treisman, a mathematics professor then at the University of California-Berkeley, established a group-based calculus honors program, reserving two-thirds of the places for minority students whose entering credentials suggested that they were at risk. The students who participated in this program ended with a higher retention rate after three years than the overall average for all university students, while minority students in a control population were mostly gone after three years. Treisman's model has been used at many institutions with comparable success (Fullilove and Treisman 1990). In another study, George (1994) tested several cooperative learning techniques on...
a predominantly African-American psychology class and compared their performance with that of a
control group taught non-cooperatively. She found that group work led to significant improvements in both
academic achievement and attitudes toward instruction.

When using cooperative learning in classes that include minority students-ethnic minorities, or women in
engineering and other nontraditionally female fields-try to avoid groups in which the minority students are
isolated. Felder et al. (1995) report a study of cooperative learning in a sequence of engineering courses.
Women responded to group work with overwhelming approval, but many indicated that they tended to
assume less active roles in group discussions and some reported that their ideas tended to be devalued
or discounted within their teams. The likelihood of these occurrences is reduced if a team contains more
than one member of the minority population.

Even though I've done everything the experts recommend, some of my students still complain that
they don't like the student-centered approach I'm using and they would have learned more if they
had taken a "normal" class.

They could be right. Students have a variety of learning styles and no instructional approach can be
optimal for everyone (Claxton and Murrell 1987; Felder 1993; Grasha 1990, 1994). In the end, despite our
best efforts, some students fail and some who pass continue to resent our putting so much of the burden
of their learning on their shoulders. One of our students once wrote in a course-end evaluation, "Felder
really makes us think!" It was on the list of things he disliked. On the other hand, for all their complaints
about how hard we are on them, our students on the average do better work than they ever did when we
just lectured, and many more of them now tell us that after getting through one of our courses they feel
confident that they can do anything. So you may lose some, but you can expect to win a lot more.

In short, we are convinced that the benefits of properly implemented student-centered instruction more
than compensate for any difficulties that may be encountered when implementing it. Instructors who
follow recommended SCI procedures when designing their courses, who are prepared for initially
negative student reactions, and who have the patience and the confidence to wait out these reactions,
will reap their rewards in more and deeper student learning and more positive student attitudes toward
their subjects and toward themselves. It may take an effort to get there, but it is an effort well worth
making.

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Of all instructional methods, lecturing is the most common, the easiest, and the least effective. Unless the instructor is a real spellbinder, most students cannot stay focused throughout a lecture: after about 10 minutes their attention begins to drift, first for brief moments and then for longer intervals; they find it increasingly hard to catch up on what they missed while their minds were wandering; and eventually they switch the lecture off altogether like a bad TV show. McKeachie [1] cites a study indicating that immediately after a lecture, students recalled 70% of the information presented in the first ten minutes and only 20% of that from the last ten minutes.

However, there are better ways; actively involving students in learning instead of simply lecturing to them leads to improved attendance, deeper questioning, higher grades, and greater lasting interest in the subject [1, 2]. A problem with active instructional methods, however, is that they sound time-consuming. Whenever I describe in workshops and seminars the proven effectiveness of in-class problem-solving, problem-formulation, trouble-shooting or brainstorming exercises, I can always count on someone in the third row asking---usually sincerely, sometimes belligerently---"If I do all that, how am I supposed to get through the syllabus?"

I have a variety of answers I trot out on such occasions, depending on my mood and the tone of my questioner, but they mostly amount to "So what if you don't?" Syllabi are usually made up from the standpoint of "What do I want to cover" rather than the much more pertinent "What do I want the students to be able to do"; when the latter approach is adopted, it often turns out that large chunks of the syllabus serve little educational purpose and can be excised with no great loss to anyone. But never mind: let's accept---for the remainder of this column, at least---the principle that it is critically important to get through the syllabus. Can I (asks my friend in the third row) use any of those allegedly powerful teaching techniques and still cover it all?

Yes (I reply), you can. Here are two techniques for doing it.

**In-class group problem-solving**

As you lecture on a body of material or go through a problem solution, instead of just posing questions to the class as a whole and enduring the subsequent embarrassing and time-wasting silences, occasionally assign a task and give the class one or two minutes to work on it in groups of three to five at their seats. For example:

- **Sketch and label a flow chart (schematic, force diagram, differential control volume) for this system.**
- **Sketch a plot of what the problem solution should look like.**
- **Give several reasons why you might need or want to know the solution.**
- **What's the next step?**
- **What's wrong with what I just wrote?**
- **How could I check this solution?**
- **What question do you have about what we just did?**
- **Suppose I run some measurements in the laboratory or plant and the results don't agree with the formula I just derived. Think of as many reasons as you can for the discrepancy.**
• What variations of this problem might I put on the next test? (This and the last one are particularly instructive.)

You don't have to spend a great deal of time on such exercises; one or two lasting no more than five minutes in a 50-minute session can provide enough stimulation to keep the class with you for the entire period. The syllabus is safe!

Warning, however, the first time you assign group work, the introverts in the class will hang back and try to avoid participating. Don't be surprised or discouraged—it's a natural response. Just get their attention—walk over to them if necessary—and remind them good-naturedly that they're supposed to be working together. When they find out that you can see them (1) they'll do it, and by the time you've done three or four such exercises most of the class will need no extra prodding. Granted, there may be a few who continue to hold out, but look at it this way: in the usual lecture approach, 5% of the students (if that many) are actively involved and 95% are not. If you can do something that reverses those percentages or comes close to it, you've got a winner.

In-class reflection and question generation

The one-minute paper is an in-class assignment in which students nominate the most important and/or the most confusing points in the lecture just concluded [3,4]. Variations of this device can be used to powerful effect. About two minutes from the end of a class, ask the students—working individually or in small groups—to write down and turn in anonymous responses to one or two of the following questions:

• What are the two most important points brought out in class today (this week, in the chapter we just finished covering)? Examination of the responses will let you know immediately whether the students are getting the essential points. Also, when the students know beforehand that this question is coming they will tend to watch for the main points as the class unfolds, with obvious pedagogical benefits.

• What were the two muddiest points in today's class (this week's classes, this section of the course)? Rank the responses in order of their frequency of occurrence and in the next class go over the ones that came up most often.

• The responses to this question will surprise you. What you would have guessed to be the most difficult concepts may not show up on many papers, if they show up at all; what will appear are concepts you take for granted, which you skimmed over in your lecture but which are unfamiliar and baffling to the students.

• What would make this material clearer to you? You also never know what you'll get in response to this one---perhaps requests for worked-out examples of solution procedures or concrete applications of abstract material, or pleas for you to write more clearly on the board, speak more slowly, or stop some annoying mannerism that you weren't aware you were doing. Responses to this question can provide valuable clues about what you could do to make your teaching more effective.

• Make up a question about an everyday phenomenon that could be answered using material presented in class today (this week). (Optional:) One or two of your questions will show up on the next test.

I used the last exercise---including the zinger about the next test---at the end of a course segment on convective heat transfer and got back a wonderful series of questions about such things as why you feel much colder in water at 20 degrees celsius than in air at the same temperature; why you feel a draft when you stand in front of a closed window on a cold day; why a fan cools you on a hot day and why a higher fan speed cools you even more; why a car windshield fogs up during the winter and how a defogger works; and why you don't get burned when you (a) move your hand right next to (but not quite touching) a pot of boiling water; (b) touch a very hot object very quickly; (c) walk across hot coals. I typed up the questions (sneaking a few additional ones onto the list) and posted them outside my office—and in the days preceding the test I had a great time watching the students thinking through all the questions and speculating on which one I would put on the test. (I used the one about the fan.)
There are other short, easy, and effective instructional methods, but these should do for starters. Check them out and let me know how they work for you. If I collect some good testimonials (positive or negative) I'll report them in a future column.

References


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The time is ripe for a closer examination of learning in college classrooms. Recent questioning of the value of higher education focuses on the worth of undergraduate education and on the quality of learning that takes place in college classrooms. In response, many colleges and universities have focused on changes that center on improving teaching and learning. In the past decade, we have seen a focus on teaching techniques in college classrooms, a movement that emphasizes active learning, the value of out-of-class learning, and the importance of assessment on college campuses. We have addressed the all-important issue of learning by college students without focusing on the all-important question of "how" our students learn academic material. One change that could begin to maximize students' learning would create "learning-centered" campuses (Barr and Tagg 1995). To create such a campus, we need to know how college students learn, to understand barriers to students' learning, and to develop classroom techniques that promote learning among college students. The keys to this knowledge lie in the fields of psychology, philosophy, and sociology; many have a basis in the study of children's learning and development, but we know much about the learning of youth and adults as well, particularly in academe.

WHAT THEORIES AND FRAMEWORKS ARE RELEVANT TO LEARNING IN COLLEGE?

Some of the many models of learning theories are particularly relevant to the traditional college classroom. For example, research shows that college students' attributions for success or failure (Weiner 1992) and their beliefs about their own abilities, or self-efficacy (Bandura 1997), influence students' motivation and goals for academic work. Moreover, some theories expand our view beyond the individual student and focus on the social context of learning. Approaches to learning that promote social constructivism, or learning within a social context, and that feature active group constructions of knowledge (Jaworski 1994) provide an ideal environment for some learners. Approaches to learning that create awareness of students' social conscience and that promote an awareness of possibilities for social transformation through action, such as conscientization (Freire and Faundez 1989), can stimulate learning, particularly for students from traditionally disadvantaged groups. And the theories of multiple intelligences (Gardner 1983) and learning styles (Kolb 1981) help us challenge time-worn assumptions about learners and learning that can exclude students and that limit our ways of thinking about the role of the college student in the classroom.

WHAT DO WE KNOW ABOUT COLLEGE STUDENTS' LEARNING?

Research tells us much about learning in college; for example, we know that students can develop realistic attributions regarding success and failure that lead to positive study behaviors when working with counselors. Researchers have also demonstrated that constructs related to self-efficacy are positively related to achievement. And in several instances, classes designed for low-achieving students that focused on developing self-efficacy as well as academic learning experienced dramatic successes. Social constructivist approaches to learning have been applied through classroom practices such as collaborative learning, problem-based learning, and peer learning groups. Most often, students who participate in these innovative instructional approaches perceive a more meaningful learning experience and in some cases actually learn more than students in conventional learning situations. Research on the application of Freire's theory of conscientization is more limited, and scholars are only beginning to apply the theory with nontraditional students and in ESL (English as a second language) courses. With regard to theories of learning styles and multiple intelligences, researchers have validated the existence of the various ways of learning and the existence of various types of intelligence. Many examples of ways to apply the theories in the classroom are available.
WHAT PRACTICES PROMOTE LEARNING AMONG COLLEGE STUDENTS?

From the literature focusing on frameworks and theories of learning, we can identify several general practices that promote learning for college students:

Social learning experiences, such as peer teaching and group projects, particularly those that promote group construction of knowledge, allow a student to observe other students' models of successful learning, and encourage him or her to emulate them (social constructivism, self-efficacy, learning styles); Varying instructional models that deviate from the lecture format, such as visual presentations, site visits, and use of the Internet (multiple intelligences, learning styles, self-efficacy); Varying expectations for students' performance, from individual written formats to group work that includes writing and presentation, interpretation of theatrical, dance, musical, or artistic work, and performance of actual tasks at a work site (attribution theory, conscientization, multiple intelligences, learning styles); Choices that allow students to capitalize on personal strengths and interests (self-efficacy, multiple intelligences, learning styles); Overt use of sociocultural situations and methods that provide authentic contexts and enculturation into an academic disciplinary community (social constructivism, conscientization); Course material that demonstrates valuing of diverse cultures, ethnic groups, classes, and genders (conscientization, learning styles).

Although it might be difficult or even impossible to incorporate all these practices into one college class, if most college classes could incorporate just a few of these elements, colleges would develop into more learning-centered communities and would move toward meeting the learning needs of a greater portion of their students.

WHAT ADDITIONAL QUESTIONS MUST BE ANSWERED?

Many important questions about college students' learning remain to be explored through research. Although we know that students' beliefs and attributions affect learning, we are not sure whether an instructor can apply techniques that will modify those beliefs and attributions to help students learn. And although literature exists to describe innovations in the classroom designed to foster learning using various models and theories, few authors have systematically tracked differences in learning across classes. Such research is needed to establish definitively the importance of these theories and models. Finally, differences in learning by gender and across racial subgroups need to be explored. Carefully designed studies employing both quantitative and naturalistic approaches are needed to help us learn more about these important topics.

REFERENCES

8. This ERIC digest is based on a full-length report in the ASHE-ERIC Higher Education Report series Volume 26, Number 4, Creating Learning Centered Classrooms: What Does Learning Theory Have to Say? by Frances K. Stage, Patricia A. Muller, Jillian A. Kinzie and Ada Simmons
EFFECTIVE LEARNING AND TEACHING

In planning instruction, effective teachers draw on a growing body of research knowledge about the nature of learning and on craft knowledge about teaching that has stood the test of time. Typically, they consider the special characteristics of the material to be learned, the background of their students, and the conditions under which the teaching and learning are to take place.

This chapter presents—non-systematically and with no claim of completeness—some principles of learning and teaching that characterize the approach of such teachers. Many of those principles apply to learning and teaching in general, but clearly some are especially important in science, mathematics, and technology education. For convenience, learning and teaching are presented here in separate sections, even though they are closely interrelated.

PRINCIPLES OF LEARNING

Learning Is Not Necessarily an Outcome of Teaching

Cognitive research is revealing that even with what is taken to be good instruction, many students, including academically talented ones, understand less than we think they do. With determination, students taking an examination are commonly able to identify what they have been told or what they have read; careful probing, however, often shows that their understanding is limited or distorted, if not altogether wrong. This finding suggests that parsimony is essential in setting out educational goals: Schools should pick the most important concepts and skills to emphasize so that they can concentrate on the quality of understanding rather than on the quantity of information presented.

What Students Learn Is Influenced by Their Existing Ideas

People have to construct their own meaning regardless of how clearly teachers or books tell them things. Mostly, a person does this by connecting new information and concepts to what he or she already believes. Concepts—the essential units of human thought—that do not have multiple links with how a student thinks about the world are not likely to be remembered or useful. Or, if they do remain in memory, they will be tucked away in a drawer labeled, say, "biology course, 1995," and will not be available to affect thoughts about any other aspect of the world. Concepts are learned best when they are encountered in a variety of contexts and expressed in a variety of ways, for that ensures that there are more opportunities for them to become imbedded in a student’s knowledge system.

But effective learning often requires more than just making multiple connections of new ideas to old ones; it sometimes requires that people restructure their thinking radically. That is, to incorporate some new idea, learners must change the connections among the things they already know, or even discard some long-held beliefs about the world. The alternatives to the necessary restructuring are to distort the new information to fit their old ideas or to reject the new information entirely. Students come to school with their own ideas, some correct and some not, about almost every topic they are likely to encounter. If their intuition and misconceptions are ignored or dismissed out of hand, their original beliefs are likely to win out in the long run, even though they may give the test answers their teachers want. Mere contradiction is not sufficient; students must be encouraged to develop new views by seeing how such views help them make better sense of the world.

Progression in Learning Is Usually From the Concrete to the Abstract

Young people can learn most readily about things that are tangible and directly accessible to their senses—visual, auditory, tactile, and kinesthetic. With experience, they grow in their ability to understand abstract concepts, manipulate symbols, reason logically, and generalize. These skills develop slowly, however, and the dependence of most people on concrete examples of new ideas persists throughout life. Concrete experiences are most effective in learning when they occur in the context of some relevant conceptual structure. The difficulties many students have in grasping abstractions are often masked by their ability to remember and recite technical terms that they do not understand. As a result, teachers—from kindergarten through college—sometimes overestimate the ability of their students to handle abstractions, and they take the students' use of the right words as evidence of understanding.
People Learn to Do Well Only What They Practice Doing

If students are expected to apply ideas in novel situations, then they must practice applying them in novel situations. If they practice only calculating answers to predictable exercises or unrealistic "word problems," then that is all they are likely to learn. Similarly, students cannot learn to think critically, analyze information, communicate scientific ideas, make logical arguments, work as part of a team, and acquire other desirable skills unless they are permitted and encouraged to do those things over and over in many contexts.

Effective Learning by Students Requires Feedback

The mere repetition of tasks by students—whether manual or intellectual—is unlikely to lead to improved skills or keener insights. Learning often takes place best when students have opportunities to express ideas and get feedback from their peers. But for feedback to be most helpful to learners, it must consist of more than the provision of correct answers. Feedback ought to be analytical, to be suggestive, and to come at a time when students are interested in it. And then there must be time for students to reflect on the feedback they receive, to make adjustments and to try again—a requirement that is neglected, it is worth noting, by most examinations—especially finals.

Expectations Affect Performance

Students respond to their own expectations of what they can and cannot learn. If they believe they are able to learn something, whether solving equations or riding a bicycle, they usually make headway. But when they lack confidence, learning eludes them. Students grow in self-confidence as they experience success in learning, just as they lose confidence in the face of repeated failure. Thus, teachers need to provide students with challenging but attainable learning tasks and help them succeed.

What is more, students are quick to pick up the expectations of success or failure that others have for them. The positive and negative expectations shown by parents, counselors, principals, peers, and—more generally—by the news media affect students' expectations and hence their learning behavior. When, for instance, a teacher signals his or her lack of confidence in the ability of students to understand certain subjects, the students may lose confidence in their ability and may perform more poorly than they otherwise might. If this apparent failure reinforces the teacher's original judgment, a disheartening spiral of decreasing confidence and performance can result.

Meaningful, Engaged Learning

In recent years, researchers have formed a strong consensus on the importance of engaged learning in schools and classrooms. This consensus, together with recognition of the changing needs of the 21st century, has stimulated the development of specific indicators of engaged learning. Jones, Valdez, Nowakowski, and Rasmussen (1994) developed the indicators described below. These indicators of engaged learning can act as a "compass" for reform instruction, helping educators chart an instructional course and maintain an orientation based on a vision of engaged learning and what it looks like in the classroom and community.

1. Indicator: Vision of Engaged Learning

What does engaged learning look like? Successful, engaged learners are responsible for their own learning. These students are self-regulated and able to define their own learning goals and evaluate their own achievement. They are also energized by their learning; their joy of learning leads to a lifelong passion for solving problems, understanding, and taking the next step in their thinking. These learners are strategic in that they know how to learn and are able to transfer knowledge to solve problems creatively. Engaged learning also involves being collaborative—that is, valuing and having the skills to work with others.

2. Indicator: Tasks for Engaged Learning

In order to have engaged learning, tasks need to be challenging, authentic, and multidisciplinary. Such tasks are typically complex and involve sustained amounts of time. They are authentic in that they
correspond to the tasks in the home and workplaces of today and tomorrow. Collaboration around authentic tasks often takes place with peers and mentors within school as well as with family members and others in the real world outside of school. These tasks often require integrated instruction that incorporates problem-based learning and curriculum by project.

3. **Indicator: Assessment of Engaged Learning**

Assessment of engaged learning involves presenting students with an authentic task, project, or investigation, and then observing, interviewing, and examining their presentations and artifacts to assess what they actually know and can do. This assessment, often called performance-based assessment, is generative in that it involves students in generating their own performance criteria and playing a key role in the overall design, evaluation, and reporting of their assessment. The best performance-based assessment has a seamless connection to curriculum and instruction so that it is ongoing. Assessment should represent all meaningful aspects of performance and should have equitable standards that apply to all students.

4. **Indicator: Instructional Models & Strategies for Engaged Learning**

The most powerful models of instruction are interactive. Instruction actively engages the learner, and is generative. Instruction encourages the learner to construct and produce knowledge in meaningful ways. Students teach others interactively and interact generatively with their teacher and peers. This allows for co-construction of knowledge, which promotes engaged learning that is problem-, project-, and goal-based. Some common strategies included in engaged learning models of instruction are individual and group summarizing, means of exploring multiple perspectives, techniques for building upon prior knowledge, brainstorming, Socratic dialogue, problem-solving processes, and team teaching.

5. **Indicator: Learning Context of Engaged Learning**

For engaged learning to happen, the classroom must be conceived of as a knowledge-building learning community. Such communities not only develop shared understandings collaboratively but also create empathetic learning environments that value diversity and multiple perspectives. These communities search for strategies to build on the strengths of all of its members. Truly collaborative classrooms, schools, and communities encourage students to ask hard questions, define problems, lead conversations, set goals, have work-related conversations with family members and other adults in and out of school, and engage in entrepreneurial activities.

6. **Indicator: Grouping for Engaged Learning**

Collaborative work that is learning-centered often involves small groups or teams of two or more students within a classroom or across classroom boundaries. Heterogeneous groups (including different sexes, cultures, abilities, ages, and socioeconomic backgrounds) offer a wealth of background knowledge and perspectives to different tasks. Flexible grouping, which allows teachers to reconfigure small groups according to the purposes of instruction and incorporates frequent heterogeneous groups, is one of the most equitable means of grouping and ensuring increased learning opportunities.

7. **Indicator: Teacher Roles for Engaged Learning**

The role of the teacher in the classroom has shifted from the primary role of information giver to that of facilitator, guide, and learner. As a facilitator, the teacher provides the rich environments and learning experiences needed for collaborative study. The teacher also is required to act as a guide—a role that incorporates mediation, modeling, and coaching. Often the teacher also is a co-learner and co-investigator with the students.

8. **Indicator: Student Roles for Engaged Learning**

One important student role is that of explorer. Interaction with the physical world and with other people allows students to discover concepts and apply skills. Students are then encouraged to reflect upon their discoveries, which is essential for the student as a cognitive apprentice. Apprenticeship takes place when students observe and apply the thinking processes used by practitioners. Students also become teachers themselves by integrating what they've learned. Hence, they become producers of knowledge, capable of making significant contributions to the world's knowledge.
Reference:


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Recommendations for Best Practice in Teaching Science

1. Students need opportunities to explore the significance of science in their lives. The goals of science should be to foster understanding, interest and appreciation of the world we live in. Besides building a knowledge base, we should also encourage the natural curiosity of students, develop the skills of procedure for investigation and solving problems, consider both the limits and possibilities of science and technology in human affairs, and build the understanding of science and technology as inquiry fields themselves.

2. Science study should involve doing science, that is, questioning and discovering – not just covering – material. The essence of science should be one of process – of inquiry and questioning. Science is something that students do, not something that is done to them by teachers presenting information and “covering” science topics. This also means activating students’ prior knowledge, encouraging questions, and helping students to research using a hands-on approach. Without minimizing the value of factual knowledge, in order to have students retain knowledge, information should be seen in the context of thought and inquiry. Teachers should model scientific thinking.

3. Effective hands-on inquiry involves a series of steps that builds students’ investigative skills. The recommended steps (order is not lockstep) are as follows: questioning - problem is introduced that incites curiosity or draws on memories of an experience with a natural phenomenon. Discussion includes what students already know or think they know and what questions they have, observation – data is gathered and a question to probe is formulated. Hypotheses are propose leading to more focused observation to test, organizing data – overlapping observation, this focuses on looking for patterns and differences, explanation – causes or theories may be used by students, reading, textbooks, teacher’s expertise may be welcomed, reflection – through reviewing the process and how any obstacles were addressed, students become more aware of the concepts they’ve learned, taking action – either by action in the larger community or with further learning. There are many process skills students learn as they carry out meaningful investigations and teachers should consult the list before using an activity to be sure that rich learning experiences are being employed.

4. Meaningful science study will aim to develop thinking, problem solving, and attitudes of curiosity, healthy skepticism, and openness to modifying explanations.

Science teachers need attitudes toward and strategies for problem solving in their teaching.

5. Science education can build a knowledge base focused on essential concepts, rather than disconnected topics or bits of information.

Teaching should be focused around broad, unifying themes, concepts and thinking. The National Science Foundation recommends five unifying concepts: Systems, order and organization; Evidence, models, and explanation; Change, consistency, and measurement; Evolution and equilibrium; Form and function.

6. Students should explore fewer topics in depth, not skim many superficially. Opt for in-depth inquiry and consequential understanding instead of the wide coverage of topics.
7. Students grow out of misconceptions and naïve theories only by actively engaging in investigation.

Only through active questioning and using actual data that contradicts prior misconceptions will students internalize accurate scientific concepts.

8. Learning science means integrating reading, writing, speaking and math. A wide range of language and numeric skills are used in an effective science program.

9. Students need to consider issues of application of science and technology. Technology addresses problems of human environmental adaptation while science attempts to answer questions about the natural world. Both influence the other.

10. Good science teaching involves facilitation, collaborative group work, and a limited, judicious use of information giving.

Teachers need to model questioning and problem solving for students to learn it (but the teacher also models not having all the answers or being an expert in all science areas). This is done through offering natural situations/puzzles that cause children to wonder. The teacher also takes on the role of facilitator – looking to see what help can be provided, being strategic in giving information to promote lifelong learning. Group work promotes discussion, thinking, and problem solving.

Meaningful assessment of students’ learning in science must promote the objectives of a good science curriculum, not undermine them.

Assessment must cause students to use thinking skills in experiential work. Authentic assessment with effective evaluation tools (checklists, rubrics, observation lists) must be used.
Chapter 7: Effective Teaching

Examples in Mathematics, and Science

(From: How People Learn: Brain, Mind, Experience, and School
John D. Bransford, Ann L. Brown, and Rodney R. Cocking, editors)

MATHEMATICS

As is the case in history, most people believe that they know what mathematics is about—computation. Most people are familiar with only the computational aspects of mathematics and so are likely to argue for its place in the school curriculum and for traditional methods of instructing children in computation. In contrast, mathematicians see computation as merely a tool in the real stuff of mathematics, which includes problem solving, and characterizing and understanding structure and patterns. The current debate concerning what students should learn in mathematics seems to set proponents of teaching computational skills against the advocates of fostering conceptual understanding and reflects the wide range of beliefs about what aspects of mathematics are important to know. A growing body of research provides convincing evidence that what teachers know and believe about mathematics is closely linked to their instructional decisions and actions (Brown, 1985; National Council of Teachers of Mathematics, 1989; Wilson, 1990a, b; Brophy, 1990; Thompson, 1992).

Teachers' ideas about mathematics, mathematics teaching, and mathematics learning directly influence their notions about what to teach and how to teach it—an interdependence of beliefs and knowledge about pedagogy and subject matter (e.g., Gamoran, 1994; Stein et al., 1990). It shows that teachers' goals for instruction are, to a large extent, a reflection of what they think is important in mathematics and how they think students best learn it. Thus, as we examine mathematics instruction, we need to pay attention to the subject-matter knowledge of teachers, their pedagogical knowledge (general and content specific), and their knowledge of children as learners of mathematics. Paying attention to these domains of knowledge also leads us to examine teachers' goals for instruction.

If students in mathematics classes are to learn mathematics with understanding—a goal that is accepted by almost everyone in the current debate over the role of computational skills in mathematics classrooms—then it is important to examine examples of teaching for understanding and to analyze the roles of the teacher and the knowledge that underlies the teacher's enactments of those roles. In this section, we examine three cases of mathematics instruction that are viewed as being close to the current vision of exemplary instruction and discuss the knowledge base on which the teacher is drawing, as well as the beliefs and goals which guide his or her instructional decisions.

MULTIPLICATION WITH MEANING

For teaching multi-digit multiplication, teacher-researcher Magdelene Lampert created a series of lessons in which she taught a heterogeneous group of 28 fourth-grade students. The students ranged in computational skill from beginning to learn the single-digit multiplication facts to being able to accurately solve n-digit by n-digit multiplications. The lessons were intended to give children experiences in which the important mathematical principles of additive and multiplicative composition, associativity, commutativity, and the distributive property of multiplication over addition were all evident in the steps of the procedures used to arrive at an answer (Lampert, 1986:316). It is clear from her description of her instruction that both her deep understanding of multiplicative structures and her knowledge of a wide range of representations and problem situations related to multiplication were brought to bear as she planned and taught these lessons. It is also clear that her goals for the lessons included not only those related to students' understanding of mathematics, but also those related to students' development as independent, thoughtful problem solvers. Lampert (1986:339) described her role as follows:
My role was to bring students' ideas about how to solve or analyze problems into the public forum of the classroom, to referee arguments about whether those ideas were reasonable, and to sanction students' intuitive use of mathematical principles as legitimate. I also taught new information in the form of symbolic structures and emphasized the connection between symbols and operations on quantities, but I made it a classroom requirement that students use their own ways of deciding whether something was mathematically reasonable in doing the work. If one conceives of the teacher's role in this way, it is difficult to separate instruction in mathematics content from building a culture of sense-making in the classroom, wherein teacher and students have a view of themselves as responsible for ascertaining the legitimacy of procedures by reference to known mathematical principles. On the part of the teacher, the principles might be known as a more formal abstract system, whereas on the part of the learners, they are known in relation to familiar experiential contexts. But what seems most important is that teachers and students together are disposed toward a particular way of viewing and doing mathematics in the classroom.

Magdelene Lampert set out to connect what students already knew about multidigit multiplication with principled conceptual knowledge. She did so in three sets of lessons. The first set used coin problems, such as "Using only two kinds of coins, make $1.00 using 19 coins," which encouraged children to draw on their familiarity with coins and mathematical principles that coin trading requires. Another set of lessons used simple stories and drawings to illustrate the ways in which large quantities could be grouped for easier counting. Finally, the third set of lessons used only numbers and arithmetic symbols to represent problems. Throughout the lessons, students were challenged to explain their answers and to rely on their arguments, rather than to rely on the teacher or book for verification of correctness. An example serves to highlight this approach; see Box 7.2.

Lampert (1986:337) concludes:

. . . students used principled knowledge that was tied to the language of groups to explain what they were seeing. They were able to talk meaningfully about place value and order of operations to give legitimacy to procedures and to reason about their outcomes, even though they did not use technical terms to do so. I took their experimentations and arguments as evidence that they had come to see mathematics as more than a set of procedures for finding answers.

Clearly, her own deep understanding of mathematics comes into play as she teaches these lessons. It is worth noting that her goal of helping students see what is mathematically legitimate shapes the way in which she designs lessons to develop students' understanding of two-digit multiplication.

UNDERSTANDING NEGATIVE NUMBERS

Helping third-grade students extend their understanding of numbers from the natural numbers to the integers is a challenge undertaken by another teacher-researcher. Deborah Ball's work provides another snapshot of teaching that draws on extensive subject content and pedagogical content knowledge. Her goals in instruction include "developing a practice that respects the integrity both of mathematics as a discipline and of children as mathematical thinkers" (Ball, 1993). That is, she not only takes into account what the important mathematical ideas are, but also how children think about the particular area of mathematics on which she is focusing. She draws on both her understanding of the integers as mathematical entities (subject-matter knowledge) and her extensive pedagogical content knowledge specifically about integers. Like Lampert, Ball's goals go beyond the boundaries of what is typically considered mathematics and include developing a culture in which students conjecture, experiment, build arguments, and frame and solve problems--the work of mathematicians.

Deborah Ball's description of work highlights the importance and difficulty of figuring out powerful and effective ways to represent key mathematical ideas to children (see Ball, 1993). A wealth of possible models for negative numbers exists and she reviewed a number of them--magic peanuts, money, game scoring, a frog on a number line, buildings with floors above and below ground. She decided to use the building model first and money later: she was acutely aware of the strengths and limitations of each model as a way for representing the key properties of numbers, particularly those of magnitude and direction. Reading Deborah Ball's description of her deliberations, one is struck by the complexity of selecting appropriate models for particular mathematical ideas and processes. She hoped that the positional aspects of the building model would help children recognize that negative numbers were not
equivalent to zero, a common misconception. She was aware that the building model would be difficult to use for modeling subtraction of negative numbers.

Deborah Ball begins her work with the students, using the building model by labeling its floors. Students readily labeled the underground floors and accepted them as "below zero." They then explored what happened as little paper people entered an elevator at some floor and rode to another floor. This was used to introduce the conventions of writing addition and subtraction problems involving integers 4 — 6 = —2 and —2 + 5 = 3. Students were presented with increasingly difficult problems. For example, "How many ways are there for a person to get to the second floor?" Working with the building model allowed students to generate a number of observations. For example, one student noticed that "any number below zero plus that same number above zero equals zero" (Ball, 1993:381). However, the model failed to allow for explorations for such problems 5 + (—6) and Ball was concerned that students were not developing a sense that —5 was less than —2—it was lower, but not necessarily less. Ball then used a model of money as a second representational context for exploring negative numbers, noting that it, too, has limitations.

Clearly, Deborah Ball's knowledge of the possible representations of integers (pedagogical content knowledge) and her understanding of the important mathematical properties of integers were foundational to her planning and her instruction. Again, her goals related to developing students' mathematical authority, and a sense of community also came into play. Like Lampert, Ball wanted her students to accept the responsibility of deciding when a solution is reasonable and likely to be correct, rather than depending on text or teacher for confirmation of correctness.

GUIDED DISCUSSION

The work of Lampert and Ball highlights the role of a teacher's knowledge of content and pedagogical content knowledge in planning and teaching mathematics lessons. It also suggests the importance of the teacher's understanding of children as learners. The concept of cognitively guided instruction helps illustrate another important characteristic of effective mathematics instruction: that teachers not only need knowledge of a particular topic within mathematics and knowledge of how learners think about the particular topic, but also need to develop knowledge about how the individual children in their classrooms think about the topic (Carpenter and Fennema, 1992; Carpenter et al., 1996; Fennema et al., 1996). Teachers, it is claimed, will use their knowledge to make appropriate instructional decisions to assist students to construct their mathematical knowledge. In this approach, the idea of domains of knowledge for teaching (Shulman, 1986) is extended to include teachers' knowledge of individual learners in their classrooms.

Cognitively guided instruction is used by Annie Keith, who teaches a combination first- and second-grade class in an elementary school in Madison Wisconsin (Hiebert et al., 1997). Her instructional practices are an example of what is possible when a teacher understands children's thinking and uses that understanding to guide her teaching. A portrait of Ms. Keith's classroom reveals also how her knowledge of mathematics and pedagogy influence her instructional decisions.

Word problems form the basis for almost all instruction in Annie Keith's classroom. Students spend a great deal of time discussing alternative strategies with each other, in groups, and as a whole class. The teacher often participates in these discussions but almost never demonstrates the solution to problems. Important ideas in mathematics are developed as students explore solutions to problems, rather than being a focus of instruction per se. For example, place-value concepts are developed as students use base-10 materials, such as base-10 blocks and counting frames, to solve word problems involving multidigit numbers.

Mathematics instruction in Annie Keith's class takes place in a number of different settings. Everyday first-grade and second-grade activities, such as sharing snacks, lunch count, and attendance, regularly serve as contexts for problem-solving tasks. Mathematics lessons frequently make use of math centers in which the students do a variety of activities. On any given day, children at one center may solve word problems presented by the teacher while at another center children write word problems to present to the class later or play a math game.
She continually challenges her students to think and to try to make sense of what they are doing in math. She uses the activities as opportunities for her to learn what individual students know and understand about mathematics. As students work in groups to solve problems, she observes the various solutions and mentally makes notes about which students should present their work; she wants a variety of solutions presented so that students will have an opportunity to learn from each other. Her knowledge of the important ideas in mathematics serves as one framework for the selection process, but her understanding of how children think about the mathematical ideas they are using also affects her decisions about who should present. She might select a solution that is actually incorrect to be presented so that she can initiate a discussion of a common misconception. Or she may select a solution that is more sophisticated than most students have used in order to provide an opportunity for students to see the benefits of such a strategy. Both the presentations of solutions and the class discussions that follow provide her with information about what her students know and what problems she should use with them next.

Annie Keith's strong belief that children need to construct their understanding of mathematical ideas by building on what they already know guides her instructional decisions. She forms hypotheses about what her students understand and selects instructional activities based on these hypotheses. She modifies her instruction as she gathers additional information about her students and compares it with the mathematics she wants them to learn. Her instructional decisions give her clear diagnoses of individual students' current state of understanding. Her approach is not a free-for-all without teacher guidance: rather, it is instruction that builds on students' understandings and is carefully orchestrated by the teacher, who is aware of what is mathematically important and also what is important to the learner's progress.

MODEL-BASED REASONING

Some attempts to revitalize mathematics instruction have emphasized the importance of modeling phenomena. Work on modeling can be done from kindergarten through twelfth grade (K-12). Modeling involves cycles of model construction, model evaluation, and model revision. It is central to professional practice in many disciplines, such as mathematics and science, but it is largely missing from school instruction. Modeling practices are ubiquitous and diverse, ranging from the construction of physical models, such as a planetarium or a model of the human vascular system, to the development of abstract symbol systems, exemplified by the mathematics of algebra, geometry, and calculus. The ubiquity and diversity of models in these disciplines suggest that modeling can help students develop understanding about a wide range of important ideas. Modeling practices can and should be fostered at every age and grade level (Clement, 1989; Hestenes, 1992; Lehrer and Romberg, 1996a, b; Schauble et al., 1995; see Box 7.3).

Taking a model-based approach to a problem entails inventing (or selecting) a model, exploring the qualities of the model, and then applying the model to answer a question of interest. For example, the geometry of triangles has an internal logic and also has predictive power for phenomena ranging from optics to wayfinding (as in navigational systems) to laying floor tile. Modeling emphasizes a need for forms of mathematics that are typically underrepresented in the standard curriculum, such as spatial visualization and geometry, data structure, measurement, and uncertainty. For example, the scientific study of animal behavior, like bird foraging, is severely limited unless one also has access to such mathematical concepts as variability and uncertainty. Hence, the practice of modeling introduces the further explorations of important "big ideas" in disciplines.

CONCLUSION

Increasingly, approaches to early mathematics teaching incorporate the premises that all learning involves extending understanding to new situations, that young children come to school with many ideas about mathematics, that knowledge relevant to a new setting is not always accessed spontaneously, and that learning can be enhanced by respecting and encouraging children to try out the ideas and strategies...
that they bring to school-based learning in classrooms. Rather than beginning mathematics instruction by focusing solely on computational algorithms, such as addition and subtraction, students are encouraged to invent their own strategies for solving problems and to discuss why those strategies work. Teachers may also explicitly prompt students to think about aspects of their everyday life that are potentially relevant for further learning. For example, everyday experiences of walking and related ideas about position and direction can serve as a springboard for developing corresponding mathematics about the structure of large-scale space, position, and direction (Lehrer and Romberg, 1996b).

As research continues to provide good examples of instruction that help children learn important mathematics, there will be better understanding of the roles that teachers' knowledge, beliefs, and goals play in their instructional thinking and actions. The examples we have provided here make it clear that the selection of tasks and the guidance of students' thinking as they work through tasks is highly dependent on teachers' knowledge of mathematics, pedagogical content knowledge, and knowledge of students in general.

SCIENCE

Two recent examples in physics illustrate how research findings can be used to design instructional strategies that promote the sort of problem-solving behavior observed in experts. Undergraduates who had finished an introductory physics course were asked to spend a total of 10 hours, spread over several weeks, solving physics problems using a computer-based tool that constrained them to perform a conceptual analysis of the problems based on a hierarchy of principles and procedures that could be applied to solve them (Dufresne et al., 1996). This approach was motivated by research on expertise (discussed in Chapter 2). The reader will recall that, when asked to state an approach to solving a problem, physicists generally discuss principles and procedures. Novices, in contrast, tend to discuss specific equations that could be used to manipulate variables given in the problem (Chi et al., 1981). When compared with a group of students who solved the same problems on their own, the students who used the computer to carry out the hierarchical analyses performed noticeably better in subsequent measures of expertise. For example, in problem solving, those who performed the hierarchical analyses outperformed those who did not, whether measured in terms of overall problem-solving performance, ability to arrive at the correct answer, or ability to apply appropriate principles to solve the problems; see Figure 7.1. Furthermore, similar differences emerged in problem categorization: students who performed the hierarchical analyses considered principles (as opposed to surface features) more often in deciding whether or not two problems would be solved similarly; see Figure 7.2. (See Chapter 6 for an example of the type of item used in the categorization task of Figure 7.2.) It is also worth noting that both Figures 7.1 and 7.2 illustrate two other issues that we have discussed in this volume, namely that time on task is a major indicator for learning and that deliberate practice is an efficient way to promote expertise. In both cases, the control group made significant improvements simply as a result of practice (time on task), but the experimental group showed more improvements for the same amount of training time (deliberate practice).

Introductory physics courses have also been taught successfully with an approach for problem solving that begins with a qualitative hierarchical analysis of the problems (Leonard et al., 1996). Undergraduate engineering students were instructed to write qualitative strategies for solving problems before attempting to solve them (based on Chi et al., 1981). The strategies consisted of a coherent verbal description of how a problem could be solved and contained three components: the major principle to be applied; the justification for why the principle was applicable; and the procedures for applying the principle. That is, the what, why, and how of solving the problem were explicitly delineated; see Box 7.4. Compared with students who took a traditional course, students in the strategy-based course performed significantly better in their ability to categorize problems according to the relevant principles that could be applied to solve them; see Figure 7.3.

Hierarchical structures are useful strategies for helping novices both recall knowledge and solve problems. For example, physics novices who had completed and received good grades in an introductory college physics course were trained to generate a problem analysis called a theoretical problem description (Heller and Reif, 1984). The analysis consists of describing force problems in terms of concepts, principles, and heuristics. With such an approach, novices substantially improved in their ability
to solve problems, even though the type of theoretical problem description used in the study was not a natural one for novices. Novices untrained in the theoretical descriptions were generally unable to generate appropriate descriptions on their own—even given fairly routine problems. Skills, such as the ability to describe a problem in detail before attempting a solution, the ability to determine what relevant information should enter the analysis of a problem, and the ability to decide which procedures can be used to generate problem descriptions and analyses, are tacitly used by experts but rarely taught explicitly in physics courses.

Another approach helps students organize knowledge by imposing a hierarchical organization on the performance of different tasks in physics (Eylon and Reif, 1984). Students who received a particular physics argument that was organized in hierarchical form performed various recall and problem-solving tasks better than subjects who received the same argument non-hierarchically. Similarly, students who received a hierarchical organization of problem-solving strategies performed much better than subjects who received the same strategies organized non-hierarchically. Thus, helping students to organize their knowledge is as important as the knowledge itself, since knowledge organization is likely to affect students' intellectual performance.

These examples demonstrate the importance of deliberate practice and of having a "coach" who provides feedback for ways of optimizing performance (see Chapter 3). If students had simply been given problems to solve on their own (an instructional practice used in all the sciences), it is highly unlikely that they would have spent time efficiently. Students might get stuck for minutes, or even hours, in attempting a solution to a problem and either give up or waste lots of time. In Chapter 3, we discussed ways in which learners profit from errors and that making mistakes is not always time wasted. However, it is not efficient if a student spends most of the problem-solving time rehearsing procedures that are not optimal for promoting skilled performance, such as finding and manipulating equations to solve the problem, rather than identifying the underlying principle and procedures that apply to the problem and then constructing the specific equations needed. In deliberate practice, a student works under a tutor (human or computer based) to rehearse appropriate practices that enhance performance. Through deliberate practice, computer-based tutoring environments have been designed that reduce the time it takes individuals to reach real-world performance criteria from 4 years to 25 hours (see Chapter 9)!

CONCEPTUAL CHANGE

Before students can really learn new scientific concepts, they often need to re-conceptualize deeply rooted misconceptions that interfere with the learning. As reviewed above (see Chapters 3 and 4), people spend considerable time and effort constructing a view of the physical world through experiences and observations, and they may cling tenaciously to those views--however much they conflict with scientific concepts--because they help them explain phenomena and make predictions about the world (e.g., why a rock falls faster than a leaf).

One instructional strategy, termed "bridging," has been successful in helping students overcome persistent misconceptions (Brown, 1992; Brown and Clement, 1989; Clement, 1993). The bridging strategy attempts to bridge from students' correct beliefs (called anchoring conceptions) to their misconceptions through a series of intermediate analogous situations. Starting with the anchoring intuition that a spring exerts an upward force on the book resting on it, the student might be asked if a book resting on the middle of a long, "springy" board supported at its two ends experiences an upward force from the board. The fact that the bent board looks as if it is serving the same function as the spring helps many students agree that both the spring and the board exert upward forces on the book. For a student who may not agree that the bent board exerts an upward force on the book, the instructor may ask a student to place her hand on top of a vertical spring and push down and to place her hand on the middle of the springy board and push down. She would then be asked if she experienced an upward force that resisted her push in both cases. Through this type of dynamic probing of students' beliefs, and by helping them come up with ways to resolve conflicting views, students can be guided into constructing a coherent view that is applicable across a wide range of contexts.

Another effective strategy for helping students overcome persistent erroneous beliefs are interactive lecture demonstrations (Sokoloff and Thornton, 1997; Thornton and Sokoloff, 1997). This strategy, which
has been used very effectively in large introductory college physics classes, begins with an introduction to a demonstration that the instructor is about to perform, such as a collision between two air carts on an air track, one a stationary light cart, the other a heavy cart moving toward the stationary cart. Each cart has an electronic "force probe" connected to it which displays on a large screen and in real-time the force acting on it during the collision. The teacher first asks the students to discuss the situation with their neighbors and then record a prediction as to whether one of the carts would exert a bigger force on the other during impact or whether the carts would exert equal forces.

The vast majority of students incorrectly predict that the heavier, moving cart exerts a larger force on the lighter, stationary cart. Again, this prediction seems quite reasonable based on experience—students know that a moving Mack truck colliding with a stationary Volkswagen beetle will result in much more damage done to the Volkswagen, and this is interpreted to mean that the Mack truck must have exerted a larger force on the Volkswagen. Yet, notwithstanding the major damage to the Volkswagen, Newton's Third Law states that two interacting bodies exert equal and opposite forces on each other.

After the students make and record their predictions, the instructor performs the demonstration, and the students see on the screen that the force probes record forces of equal magnitude but oppositely directed during the collision. Several other situations are discussed in the same way: What if the two carts had been moving toward each other at the same speed? What if the situation is reversed so that the heavy cart is stationary and the light cart is moving toward it? Students make predictions and then see the actual forces between the carts displayed as they collide. In all cases, students see that the carts exert equal and opposite forces on each other, and with the help of a discussion moderated by the instructor, the students begin to build a consistent view of Newton's Third Law that incorporates their observations and experiences.

Consistent with the research on providing feedback (see Chapter 3), there is other research that suggests that students' witnessing the force displayed in real-time as the two carts collide helps them overcome their misconceptions; delays of as little as 20-30 minutes in displaying graphic data of an event occurring in real-time significantly inhibits the learning of the underlying concept (Brasell, 1987).

Both bridging and the interactive demonstration strategies have been shown to be effective at helping students permanently overcome misconceptions. This finding is a major breakthrough in teaching science, since so much research indicates that students often can parrot back correct answers on a test that might be erroneously interpreted as displaying the eradication of a misconception, but the same misconception often resurfaces when students are probed weeks or months later (see Mestre, 1994, for a review).

TEACHING AS COACHING

One of the best examples of translating research into practice is Minstrell's (1982, 1989, 1992) work with high school physics students. Minstrell uses many research-based instructional techniques (e.g., bridging, making students' thinking visible, facilitating students' ability to restructure their own knowledge) to teach physics for understanding. He does this through classroom discussions in which students construct understanding by making sense of physics concepts, with Minstrell playing a coaching role. The following quote exemplifies his innovative and effective instructional strategies (Minstrell, 1989:130-131):

Students' initial ideas about mechanics are like strands of yarn, some unconnected, some loosely interwoven. The act of instruction can be viewed as helping the students unravel individual strands of belief, label them, and then weave them into a fabric of more complete understanding. An important point is that later understanding can be constructed, to a considerable extent, from earlier beliefs. Sometimes new strands of belief are introduced, but rarely is an earlier belief pulled out and replaced. Rather than denying the relevancy of a belief, teachers might do better by helping students differentiate their present ideas from and integrate them into conceptual beliefs more like those of scientists.

Describing a lesson on force, Minstrell (1989:130-131) begins by introducing the topic in general terms:

Today we are going to try to explain some rather ordinary events that you might see any day. You will find that you already have many good ideas that will help explain those events. We will find that some of our ideas are similar to those of the scientist, but in other cases our ideas might be different. When we are finished with this unit, I
expect that we will have a much clearer idea of how scientists explain those events, and I know that you will feel more comfortable about your explanations . . . A key idea we are going to use is the idea of force. What does the idea of force mean to you?

Many views emerge from the ensuing classroom discussion, from the typical "push or pull" to descriptions that include sophisticated terms, such as energy and momentum. At some point Minsrell guides the discussion to a specific example: he drops a rock and asks students how the event can be explained using their ideas about force. He asks students to individually formulate their ideas and to draw a diagram showing the major forces on the rock as arrows, with labels to denote the cause of each force. A lengthy discussion follows in which students present their views, views that contain many irrelevant (e.g., nuclear forces) or fictitious forces (e.g., the spin of the earth, air). In his coaching, Minsrell asks students to justify their choices by asking questions, such as "How do you know?" "How did you decide?" "Why do you believe that?"

With this approach, Minsrell has been able to identify many erroneous beliefs of students that stand in the way of conceptual understanding. One example is the belief that only active agents (e.g., people) can exert forces, that passive agents (e.g., a table) cannot. Minsrell (1992) has developed a framework that helps both to make sense of students' reasoning and to design instructional strategies. (For a related theoretical framework for classifying and explaining student reasoning, see the discussion of "phenomenological primitives" in DiSessa, 1988, 1993.) Minsrell describes identifiable pieces of students' knowledge as "facets," a facet being a convenient unit of thought, a piece of knowledge, or a strategy seemingly used by the student in addressing a particular situation. Facets may relate to conceptual knowledge (e.g., passive objects do not exert force), to strategic knowledge (e.g., average velocity can be determined by adding the initial and final velocities and dividing by two), or generic reasoning (e.g., the more the X, the more the Y). Identifying students' facets, what cues them in different contexts, and how students use them in reasoning are all helpful in devising instructional strategies.

INTERACTIVE INSTRUCTION IN LARGE CLASSES

One of the obstacles to instructional innovation in large introductory science courses at the college level is the sheer number of students who are taught at one time. How does an instructor provide an active learning experience, provide feedback, accommodate different learning styles, make students' thinking visible, and provide scaffolding and tailored instruction to meet specific student needs when facing more than 100 students at a time? Classroom communication systems can help the instructor of a large class accomplish these objectives. One such system, called Classstalk, consists of both hardware and software that allows up to four students to share an input device (e.g., a fairly inexpensive graphing calculator) to "sign on" to a classroom communication network that permits the instructor to send questions for students to work on and permits students to enter answers through their input device. Answers can then be displayed anonymously in histogram form to the class, and a permanent record of each student's response is recorded to help evaluate progress as well as the effectiveness of instruction.

This technology has been used successfully at the University of Massachusetts-Amherst to teach physics to a range of students, from non-science majors to engineering and science majors (Dufresne et al., 1996; Wenk et al., 1997; Mestre et al., 1997). The technology creates an interactive learning environment in the lectures: students work collaboratively on conceptual questions, and the histogram of students' answers is used as a visual springboard for classwide discussions when students defend the reasoning they used to arrive at their answers. This technology makes students' thinking visible and promotes critical listening, evaluation, and argumentation in the class. The teacher is a coach, providing scaffolding where needed, tailoring "mini-lectures" to clear up points of confusion, or, if things are going well, simply moderating the discussion and allowing students to figure out things and reach consensus on their own. The technology is also a natural mechanism to support formative assessment during instruction, providing both the teacher and students with feedback on how well the class is grasping the concepts under study. The approach accommodates a wider variety of learning styles than is possible by lectures and helps to foster a community of learners focused on common objectives and goals.

SCIENCE FOR ALL CHILDREN

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The examples above present some effective strategies for teaching and learning science for high school and college students. We drew some general principles of learning from these examples and stressed that the findings consistently point to the strong effect of knowledge structures on learning. These studies also emphasize the importance of class discussions for developing a language for talking about scientific ideas, for making students’ thinking explicit to the teacher and to the rest of the class, and for learning to develop a line of argumentation that uses what one has learned to solve problems and explain phenomena and observations.

The question that immediately occurs is how to teach science to younger children or to students who are considered to be educationally "at risk." One approach that has been especially useful in science teaching was developed with language-minority grade-school children: Chèche Konnen, which in Haitian Creole means search for knowledge (Rosebery et al., 1992). The approach stresses how discourse is a primary means for the search for knowledge and scientific sense-making. It also illustrates how scientific ideas are constructed. In this way it mirrors science, in the words of Nobel Laureate Sir Peter Medawar (1982:111):

Like other exploratory processes, [the scientific method] can be resolved into a dialogue between fact and fancy, the actual and the possible; between what could be true and what is in fact the case. The purpose of scientific enquiry is not to compile an inventory of factual information, nor to build up a totalitarian world picture of Natural Laws in which every event that is not compulsory is forbidden. We should think of it rather as a logically articulated structure of justifiable beliefs about a Possible World--a story which we invent and criticize and modify as we go along, so that it ends by being, as nearly as we can make it, a story about real life.

The Chèche Konnen approach to teaching began by creating "communities of scientific practice" in language-minority classrooms in a few Boston and Cambridge, MA public schools. "Curriculum" emerges in these classrooms from the students' questions and beliefs and is shaped in ongoing interactions that include both the teacher and students. Students explore their own questions, much as we described above in Barb Johnson's class. In addition, students design studies, collect information, analyze data and construct evidence, and they then debate the conclusions that they derive from their evidence. In effect, the students build and argue about theories; see Box 7.5.

Students constructed scientific understandings through an iterative process of theory building, criticism, and refinement based on their own questions, hypotheses, and data analysis activities. Question posing, theorizing, and argumentation formed the structure of the students' scientific activity. Within this structure, students explored the implications of the theories they held, examined underlying assumptions, formulated and tested hypotheses, developed evidence, negotiated conflicts in belief and evidence, argued alternative interpretations, provided warrants for conclusions, and so forth. The process as a whole provided a richer, more scientifically grounded experience than the conventional focus on textbooks or laboratory demonstrations.

The emphasis on establishing communities of scientific practice builds on the fact that robust knowledge and understandings are socially constructed through talk, activity, and interaction around meaningful problems and tools (Vygotsky, 1978). The teacher guides and supports students as they explore problems and define questions that are of interest to them. A community of practice also provides direct cognitive and social support for the efforts of the group's individual members. Students share the responsibility for thinking and doing; they distribute their intellectual activity so that the burden of managing the whole process does not fall to any one individual. In addition, a community of practice can be a powerful context for constructing scientific meanings. In challenging one another's thoughts and beliefs, students must be explicit about their meanings; they must negotiate conflicts in belief or evidence; and they must share and synthesize their knowledge to achieve understanding (Brown and Palincsar, 1989; Inagaki and Hatano, 1987).

What do students learn from participating in a scientific sense-making community? Individual interviews with students before and after the water taste test investigation (see Box 7.4), first in September and again the following June, showed how the students’ knowledge and reasoning changed. In the interviews (conducted in Haitian Creole), the students were asked to think aloud about two open-ended real-world problems--pollution in the Boston Harbor and a sudden illness in an elementary school. The researchers were interested in changes in students' conceptual knowledge about aquatic ecosystems and in students'
uses of hypotheses, experiments, and explanations to organize their reasoning (for a complete discussion, see Rosebery et al., 1992).

**Conceptual Knowledge**

Not surprisingly, the students knew more about water pollution and aquatic ecosystems in June than they did in September. They were also able to use this knowledge generatively. One student explained how she would clean the water in Boston Harbor (Rosebery et al., 1992:86).

Like you look for the things, take the garbage out of the water, you put a screen to block all the paper and stuff, then you clean the water; you put chemical products in it to clean the water, and you'd take all the microscopic life out. Chlorine and alum, you put in the water. They'd gather the little stuff, the little stuff would stick to the chemical products, and they would clean the water.

Note that this explanation contains misconceptions. By confusing the cleaning of drinking water with the cleaning of sea water, the student suggests adding chemicals to take all microscopic life from the water (good for drinking water, but bad for the ecosystem of Boston Harbor). This example illustrates the difficulties in transferring knowledge appropriately from one context to another (see Chapter 3). Despite these shortcomings, it is clear that this student is starting on the path to scientific thinking, leaving behind the more superficial "I'd take all the bad stuff out of the water" type of explanation. It is also clear that by making the student's thinking visible, the teacher is in an excellent position to refine her (and perhaps the class's) understanding.

**SCIENTIFIC THINKING**

Striking changes appeared in students' scientific reasoning. In September, there were three ways in which the students showed little familiarity with scientific forms of reasoning. First, the students did not understand the function of hypotheses or experiments in scientific inquiry. When asked for their ideas about what could be making the children sick, the students tended, with few exceptions, to respond with short, unelaborated, often untestable "hypotheses" that simply restated the phenomena described in the problem: "That's a thing . . . . Ah, I could say a person, some person that gave them something . . . . Anything, like give poison to make his stomach hurt" (Rosebery et al., 1992:81).

Second, the students conceptualized evidence as information they already knew, either through personal experience or second-hand sources, rather than data produced through experimentation or observation. When asked to generate an experiment to justify an hypothesis--"How would you find out?"--they typically offered declarations: "Because the garbage is a poison for them . . . . The garbage made the fish die" (Rosebery et al., 1992:78).

Third, the students interpreted an elicitation for an experiment--"How would you be sure?"--as a text comprehension question for which there was a "right" answer. They frequently responded with an explanation or assertion of knowledge and consistently marked their responses as explanatory ("because"): "Because fish don't eat garbage. They eat plants under the water" (page 78).

In the June interviews, the students showed that they had become familiar with the function of hypotheses and experiments and with reasoning within larger explanatory frameworks. Elinor had developed a model of an integrated water system in which an action or event in one part of the system had consequences for other parts (Rosebery et al., 1992:87):

You can't leave [the bad stuff] on the ground. If you leave it on the ground, the water that, the earth has water underground, it will still spoil the water underground. Or when it rains it will just take it and, when it rains, the water runs, it will take it and leave it in the river, in where the water goes in. Those things, poison things, you aren't supposed to leave it on the ground.

In June, the students no longer invoked anonymous agents, but put forward chains of hypotheses to explain phenomena, such as why children were getting sick (page 88):

Like, you could test what the kids ate and, like, test the water, too; it could be the water that isn't good, that has microbes, that might have microscopic animals in it to make them sick.
The June interviews also showed that students had begun to develop a sense of the function and form of experimentation. They no longer depended on personal experience as evidence, but proposed experiments to test specific hypotheses. In response to a question about sick fish, Laure clearly understands how to find a scientific answer (page 91):

I'd put a fish in fresh water and one fish in a water full of garbage. I'd give the fresh water fish food to eat and the other one in the nasty water, I'd give it food to eat to see if the fresh water, if the one in the fresh water would die with the food I gave it, if the one in the dirty water would die with the food I gave it. . . . I would give them the same food to see if the things they eat in the water and the things I give them now, which will make them healthy and which wouldn't make them healthy.

CONCLUSION

Teaching and learning in science have been influenced very directly by research studies on expertise (see Chapter 2). The examples discussed in this chapter focus on two areas of science teaching: physics and junior high school biology. Several of the teaching strategies illustrated ways to help students think about the general principles or "big" ideas in physics before jumping to formulas and equations. Others illustrate ways to help students engage in deliberate practice (see Chapter 3) and to monitor their progress.

Learning the strategies for scientific thinking have another objective: to develop thinking acumen needed to promote conceptual change. Often, the barrier to achieving insights to new solutions is rooted in a fundamental misconception about the subject matter. One strategy for helping students in physics begins with an "anchoring intuition" about a phenomenon and then gradually bridging it to related phenomena that are less intuitive to the student but involve the same physics principles. Another strategy involves the use of interactive lecture demonstrations to encourage students to make predictions, consider feedback, and then reconceptualize phenomena.

The example of Chèche Konnen demonstrates the power of a sense-making approach to science learning that builds on the knowledge that students bring with them to school from their home cultures, including their familiar discourse practices. Students learned to think, talk, and act scientifically, and their first and second languages mediated their learning in powerful ways. Using Haitian Creole, they designed their studies, interpreted data, and argued theories; using English, they collected data from their mainstream peers, read standards to interpret their scientific test results, reported their findings, and consulted with experts at the local water treatment facility.

OVERALL CONCLUSION

Outstanding teaching requires teachers to have a deep understanding of the subject matter and its structure, as well as an equally thorough understanding of the kinds of teaching activities that help students understand the subject matter in order to be capable of asking probing questions.

Numerous studies demonstrate that the curriculum and its tools, including textbooks, need to be dissected and discussed in the larger contexts and framework of a discipline. In order to be able to provide such guidance, teachers themselves need a thorough understanding of the subject domain and the epistemology that guides the discipline (for history, see Wineburg and Wilson, 1988; for math and English, see Ball, 1993; Grossman et al., 1989; for science, see Rosebery et al., 1992).

The examples in this chapter illustrate the principles for the design of learning environments that were discussed in Chapter 6: they are learner, knowledge, assessment, and community centered. They are learner centered in the sense that teachers build on the knowledge students bring to the learning situation. They are knowledge centered in the sense that the teachers attempt to help students develop an organized understanding of important concepts in each discipline. They are assessment centered in the sense that the teachers attempt to make students' thinking visible so that ideas can be discussed and clarified, such as having students (1) present their arguments in debates, (2) discuss their solutions to
problems at a qualitative level, and (3) make predictions about various phenomena. They are community
centered in the sense that the teachers establish classroom norms that learning with understanding is
valued and students feel free to explore what they do not understand.

These examples illustrate the importance of pedagogical content knowledge to guide teachers. Expert
teachers have a firm understanding of their respective disciplines, knowledge of the conceptual barriers
that students face in learning about the discipline, and knowledge of effective strategies for working with
students. Teachers' knowledge of their disciplines provides a cognitive roadmap to guide their
assignments to students, to gauge student progress, and to support the questions students ask. The
teachers focus on understanding rather than memorization and routine procedures to follow, and they
engage students in activities that help students reflect on their own learning and understanding.

The interplay between content knowledge and pedagogical knowledge illustrated in this chapter
contradicts a commonly held misconception about teaching—that effective teaching consists of a set of
general teaching strategies that apply to all content areas. This notion is erroneous, just as is the idea
that expertise in a discipline is a general set of problem-solving skills that lack a content knowledge base
to support them (see Chapter 2).

The outcomes of new approaches to teaching as reflected in the results of summative assessments are
encouraging. Studies of students' discussions in classrooms indicate that they learn to use the tools of
systematic inquiry to think historically, mathematically, and scientifically. How these kinds of teaching
strategies reveal themselves on typical standardized tests is another matter. In some cases there is
evidence that teaching for understanding can increase scores on standardized measures (e.g., Resnick
et al., 1991); in other cases, scores on standardized tests are unaffected, but the students show sizable
advantages on assessments that are sensitive to their comprehension and understanding rather than
reflecting sheer memorization (e.g., Carpenter et al., 1996; Secules et al., 1997).

It is noteworthy that none of the teachers discussed in this chapter felt that he or she was finished
learning. Many discussed their work as involving a lifelong and continuing struggle to understand and
improve. What opportunities do teachers have to improve their practice? The next chapter explores
teachers' chances to improve and advance their knowledge in order to function as effective professionals.