QUESTION DRIVEN INSTRUCTION: TEACHING SCIENCE (WELL) WITH AN AUDIENCE RESPONSE SYSTEM

Ian D. Beatty, William J. Leonard, William J. Gerace, and Robert J. Dufresne

Physics Education Research Group
Scientific Reasoning Research Institute & Department of Physics
University of Massachusetts
Amherst, Massachusetts, USA

INTRODUCTION

Educational use of audience response systems (ARSs), a.k.a. "classroom response systems," is exploding in high schools and universities. One vendor claims over a million of their system's keypads have been used, in all 50 U.S. states and 10 countries worldwide, in thousands of K-12 schools and hundreds of universities (eInstruction, 2005). Several universities are beginning centralized programs to introduce and coordinate response system use across campus. A fringe technology ten years ago, ARS are entering the mainstream.

ARS have the potential to radically alter the instructional dynamic of our classrooms and impact student learning. However, for an instructor to realize this potential requires much more than merely learning to operate the technology. Response systems are a tool, not a solution. Their benefits are not conferred automatically; *how* they are used matters tremendously. To be fully effective, their use must be integrated into a larger, coherent pedagogic approach.

As part of the UMass Physics Education Research Group (UMPERG), we have worked with response systems for over a decade. In 1993 we began using *Classtalk*, a groundbreaking "classroom communication system" by Better Education Inc. In 1994 we received a U.S. National Science Foundation (NSF) grant (DUE-9453881) to deploy, develop pedagogy for, and study the impact of *Classtalk* (Dufresne *et al.*, 1996). In 1998 we began *Assessing-to-Learn*, an NSF-funded project (ESI-9730438) to seed response systems in secondary school physics classrooms and help teachers develop suitable pedagogic skills and perspectives (Beatty, 2000; Feldman & Capobianco, 2003). In 1999 we brought EduCue *PRS* (since purchased by GTCO CalComp and renamed *InterWrite PRS*) to UMass and began its dissemination across campus. As a sequel to *Assessing-to-Learn*, we are beginning a five-year NSF-funded project (ESI-0456124) to research secondary school science teachers' learning of response system pedagogy. Based on twelve years of experience with ARS — teaching, researching, and mentoring — we have developed a comprehensive perspective on the effective use of such systems for the teaching of science at both the secondary school and university levels.

In this chapter we will introduce that perspective. We will not attempt to describe how response systems work, report our personal experiences using them, or discuss detailed

Chapter 7 of *Audience Response Systems in Higher Education: Applications and Cases*, edited by David A. Banks. Idea Group Inc., Hershey PA. ISBN 1-59140-947-0 (hardcover), 1-59140-948-9 (paperback), 1-59140-949-7 (e-book). Preprint.

logistical issues. Other chapters in this volume address those topics, and we have addressed them elsewhere (Beatty, 2004; Dufresne & Gerace, 2004; Dufresne *et al.*, 2001a; Dufresne *et al.*, 1996; Dufresne *et al.*, 2000; Dufresne *et al.*, 2002b; Gerace *et al.*, 2000; Leonard *et al.*, 2001; Leonard *et al.*, 1999). Rather, we will present *Question Driven Instruction* (QDI), a coherent, ARS-based pedagogic approach to teaching with an audience response system. We want to raise the level of discussion from “how to use the tool” to “what to do with the tool.”

Section 2 motivates and introduces QDI. Section 3 describes what QDI “looks like” in practice. Section 4 provides some advice for attempting QDI. The final section presents a brief summary and some parting thoughts. We will confine our discussion to the teaching of science, because that is the domain of our expertise, but we believe many of the ideas presented have wider applicability.

WHY PRACTICE QUESTION DRIVEN INSTRUCTION?

Most science instructors would agree that their ultimate objective is not to teach students to recite memorized facts or solve a narrow set of rehearsed problem types. Rather, they hope to inculcate an integrated understanding of the subject’s conceptual foundation, the ability to reason from that foundation, the capacity to solve a broad range of problems including types never before encountered, and knowledge that endures long after the course has ended. Traditional instructional modes, centered on lecture-style “transmissionist” teaching and drill-and-practice, are demonstrably poor at achieving such an objective (Hake, 1998; Hestenes *et al.*, 1992; McDermott, 1991, 1993; Mestre, 1991; Redish & Steinberg, 1999).

Active Learning and Audience Response Systems

As a response to the ineffectiveness of traditional instruction, the science education research community has promoted the concept of *active learning* (Bonwell & Eison, 1991; Laws, 1997). For learners to develop robust, durable, transferable knowledge of a complex subject, they must actively engage in certain kinds of mental activity. Information may be transmitted to students from teachers, textbooks, and websites, but knowledge must be constructed by each individual. Knowledge construction involves integrating new concepts into one’s existing knowledge structure, and reevaluating and reordering that structure as one’s perspective evolves (Cheek, 1992; Fosnot, 1993; O'Loughlin, 1993; von Glasersfeld, 1991, 1992, 1998). Even at the “beginning” of learning about a subject, new knowledge must be integrated with informal preconceptions, especially in science disciplines (Mestre, 1994).

“Active learning” describes the approach of having students engage in effortful, directed cognitive activity in order to assimilate and refine new ideas and structure their knowledge. The term was invented to push against the notion that students should attempt to absorb everything a teacher or textbook presents, that a teacher’s responsibility is to declaratively present the content of the subject at hand, and that drill-and-practice is an effective learning strategy.

Audience response systems are frequently used as a tool to engender active learning in the classroom (Mazur, 1997; Milner-Bolotin, 2004; Penuel *et al.*, 2004). The idea is that by having students think about and answer questions, and discuss them within small groups or as a class, their minds will engage with the material and active learning will happen. Research suggests that this expectation is generally fulfilled (Hake, 1998).

A Model of Beneficial Learning Environments

How People Learn, a landmark 1999 research review by the U.S. National Research Council (Bransford *et al.*, 1999), argues that effective learning environments ought to be *student-centered*, *knowledge-centered*, *assessment-centered*, and *community-centered*. This perspective helps us understand and maximize the effectiveness of ARS-based instruction.

A *student-centered* learning environment recognizes that students' preexisting knowledge and beliefs are the lens through which all subsequent experiences are perceived. It also acknowledges that individual students begin with different knowledge, progress along different learning paths at different rates, and have different strengths, weaknesses, and learning styles. A truly student-centered environment does not merely concede these truths and occasionally attack a common misconception, but rather is built from the ground up to interact with students as individuals, coaching them from their varied initial states to the intended goal by whatever unique trajectory each requires. We would extend the idea of a student-centered learning environment to recognize the critical role played by students' degree of introspection, motivation, and personal investment. Therefore, learning and communication should themselves be prominent topics of attention alongside the subject's content material.

A *knowledge-centered* learning environment treats knowledge not as a collection of ideas, facts, and skills, but rather as a rich, interconnected structure that must be organized and refined as it is expanded. It treats information as the raw material of useful knowledge rather than as something to be acquired for its own merits.

An *assessment-centered* learning environment recognizes that continual, detailed feedback is essential to guide students in the learning process and instructors in the teaching process, and weaves *formative assessment* deeply into the fabric of instruction. Formative assessment means using assessment (measurement) of student knowledge *during* instruction in order to provide immediate, guiding feedback for students and teachers. This is in contrast to *summative assessment*, in which testing is used *after* instruction to gauge how much students have learned. The primary objective of formative assessment is learning; the primary objective of summative assessment is evaluation. Formative assessment is perhaps the most successful instructional "innovation" ever (Bell & Cowie, 2001; Black & Wiliam, 1988a, 1988b; Boston, 2002; Hobson, 1997).

A *community-centered* learning environment recognizes that students belong to communities of co-learners at the course, program, institution, and society levels, and promotes constructive interaction between individuals to further learning. In particular, it encourages students to view each other as compatriots rather than competitors, and takes advantage of the pedagogic benefits of cooperative activity, disagreement resolution, and articulation of ideas.

As Roschelle and collaborators have noted (Roschelle, 2003; Roschelle *et al.*, 2004), ARS use tends to transform the classroom dynamic in a way that makes instruction more student-centered, knowledge-centered, assessment-centered, and community-centered. To put it simply, an ARS can be used for frequent formative assessment (assessment-centered) that lets teaching and learning be tuned to the needs of individual students (student-centered). As students ponder questions and engage in dialogue with each other and the instructor (community-centered), they are building and enriching a network of structured, useful, principle-based knowledge (knowledge-centered). In general, using an ARS in a way that enhances these aspects increases teaching effectiveness, while using one in a way that dilutes them undermines it.

Question Driven Instruction

Active learning and strengthening of the "four centerednesses" is a possible outcome of ARS use, but it is not automatic. Furthermore, the degree to which these are achieved — impacting the quality of student learning — depends on how an instructor makes use of an ARS.

An ARS is a tool that can be used for many different, sometimes incompatible ends. It can be used as an attendance-taker, coercing students' presence in class. It can be used as a delivery system for quizzes, testing students' comprehension of assigned reading. It can be used to punctuate lecture with opportunities for student thinking, encouraging attention and engagement. It can be used to spur inter-student discussion, promoting sharing of knowledge. It can be used to gauge students' initial understanding of a topic, influencing subsequent coverage.

We see a much more ambitious possibility: that ARS-based questioning can become the very core of classroom instruction, replacing the "transmit and test" paradigm with a cyclic process of question posing, deliberation, commitment to an answer, and discussion. We call this *Question Driven Instruction* (QDI).

Our perspective on QDI derives from years of research and development work in multiple contexts (Dufresne & Gerace, 2004; Dufresne *et al.*, 2002a; Dufresne *et al.*, 2001a; Dufresne *et al.*, 1996; Dufresne *et al.*, 2000, 2001b; Dufresne *et al.*, 1992, 2002b; Gerace, 1992; Gerace *et al.*, 1997; Gerace *et al.*, 2000; Leonard *et al.*, 2001; Mestre *et al.*, 2001). "Question driven" refers to the fact that we place the posing, answering, and discussing of questions via response system at the center of the instructional dynamic, to act as an engine of engagement and learning. "Active learning" is the student's end of the dynamic, and "agile teaching" is the instructor's (see Figure 1). "Active learning" has been introduced above. "Agile teaching" refers to the practice of teaching with a very tight feedback loop, almost continually probing students to ascertain and monitor their learning progress and difficulties. It means modeling them as an array of diverse individuals with diverse needs and making minute-by-minute decisions about what actions to take to maintain an optimally beneficial learning environment. This contrasts with the common practice of teaching according to a "ballistic" lesson plan: designing a plan for an entire class meeting, "launching" the plan, hoping that it hits reasonably close to its target, and waiting for the next exam to know for certain.

Figure 1: A representation of Question Driven Instruction.

Question Driven Instruction is a perspective, an instructional style, and a set of pedagogic techniques. It is founded upon the following beliefs.

- The primary goal of instruction is a rich, deep, robust, durable understanding of the subject's essential content from which the student can reason, not "coverage" of a prescribed list of topics.
- Learning is a multi-pass process, during which ideas must be revisited several times in varying contexts and with varying degrees of sophistication to build structured, expert-like knowledge. Students should not be expected to fully grasp any idea or topic on their first exposure.
- The construction of understanding is an effortful process that necessarily involves confusion, frustration, conflict resolution, and unlearning undesirable ideas. Perfect instruction that makes a subject obvious and learning easy is unachievable.
- Instructors must do more than simply present and expound upon knowledge they wish students to master. For efficient learning, they must actively seek out and destroy the impediments to student's understanding: conflicting notions, missing or weak foundational concepts and skills, unhelpful perspectives, and the like.
- Correctly predicting any one student's response to an instructional stimulus is difficult; doing so for an ensemble of students in a class is impossible. An instructor must continually probe, monitor, and model students' knowledge state, progress, and difficulties on a minute-by-minute time scale, and adjust teaching behavior accordingly.
- The very act of articulating an idea or argument, whether correct or incorrect, is of value to both the speaker and to listeners. Analysis of such articulations and resolution of conflicts between different students' statements adds significant value, even when an instructor is not participating.
- An instructor cannot provide enough customized interaction with each student in a moderate-sized or large class for efficient learning, and so must foster interaction and cooperative learning among students. Small-group activity and class-wide discussion are both valuable.

- The most potent way to foster learning is to empower students by providing them with the skills and perspective to assess their own knowledge and learning and to actively seek out beneficial activity and stimulus. In this way, the instructor becomes a learning coach rather than a content provider.

Formative assessment is central to the approach: it provides students with feedback to guide their learning activities, and provides instructors with feedback to guide their teaching decisions. In particular, we use an ARS to implement *real-time formative assessment*, in which instructor and students gain minute-to-minute feedback, enabling productive student engagement and the high level of responsiveness sought by the agile teacher.

WHAT DOES *QUESTION DRIVEN INSTRUCTION* LOOK LIKE?

The Curriculum

From a high-level vantage, the curriculum of a course taught according to QDI principles need not look much different from that of a traditionally taught course. QDI is a perspective on methodology, not on content. However, instructors who adjust topic coverage to students' learning progress often find that over time, they devote more of a course to building solid understanding of core concepts, and less to peripheral or advanced topics. This does not mean that students learn less about these topics. One of the most powerful effects formative assessment has on instructors is to shatter their illusions that student learning correlates with "coverage" of material. It reveals just how much of what an instructor presents is never really understood or retained by most students.

Additionally, a linear course syllabus only crudely approximates the multi-pass learning that occurs during effective QDI. Recognizing that students are building and reorganizing a complex and richly cross-linked knowledge structure, an instructor will frequently include forward and backward references connecting current topics to future and past ones. At times, occurrences in a classroom will cause an instructor to revisit and redevelop prior ideas, not just to "do it again" and hope students "get it this time," but to let students reconsider the ideas from a broader, more sophisticated perspective.

The Classroom

To the uninitiated, a QDI classroom may seem chaotic. QDI treats the instructional process as a collection of dialogues: between the teacher and the class, between the teacher and individual students in the class, and between students. This tends to make the QDI classroom a noisy place. Side chatter among students generally indicates discussion about some point raised by the course — active engagement.

Furthermore, a QDI instructor does not follow a ballistic lesson plan, but continually probes the class for clues about how best to proceed towards a general objective. To an observer accustomed to polished presentations, QDI may appear meandering or even floundering. The QDI instructor is in fact following a circuitous and improvised route to shepherd students along, whereas the traditional lecturer is traveling a relatively straight path to a destination whether or not students follow.

A central tenet of QDI is that an instructor must continually probe students for clues; construct, correct, refine, and evolve a model of their changing knowledge states and difficulties; and decide what instructional actions that model indicates. Most teachers unconsciously practice this in one-on-one tutoring or with sufficiently small groups. Some innately adept instructors can also manage this with a dozen or twenty students, but many of us cannot effectively communicate with and model so many individuals. Instead, we fall back on teaching to the mean and rely on occasional questions, eye contact, and body language for guidance. In large university lectures, most of us give up on even that and present a truly ballistic lecture. This is the “scaling problem” of QDI: it depends on an instructor’s ability to communicate with individual students and model their learning and needs, which an unassisted instructor can only manage for small numbers of students.

Realizing QDI in a full-sized class depends on having and using an audience response system of some kind. Response systems present a partial solution to this scaling problem by providing a supplemental, technology-mediated channel of communication between an instructor and students, helping the instructor assess student understanding, maintain student engagement in the questioning process, and manage the classroom interaction. An ARS can also help with time management in the classroom and improve the efficiency of interactive, formative assessment-based instruction. More sophisticated response systems called *classroom communication systems*, such as the venerable and now discontinued *Classtalk*, provide additional helpful capabilities such as self-paced question sets, open-ended question types, and — most importantly — support for collective answers from small collaborative student groups (Roschelle *et al.*, 2004).

A Class Session

A typical QDI class session is organized around a *question cycle*, represented in Figure 2. The instructor begins by presenting a question or problem to the students and giving them a few minutes to discuss it among themselves. (Note that we do *not* begin with a lecture.) Students then enter responses into the ARS, and the instructor displays a histogram of class-wide results for all to see. Without revealing the correctness of any answers, she solicits volunteers to argue for the various answers and moderates a class-wide discussion. Her immediate objective is to draw out students’ reasoning and vocabulary, expose students to each others’ ideas, and make implicit assumptions explicit — *not* to tell students whether their answers and arguments are correct. This may seem inefficient, but allowing students to confront other conceptions and sort out contradictions in their own vocabulary is the fastest, most durable way to build understanding. And helping students develop a general understanding of the subject matter, not just learn the answer to the immediate question, is the instructor’s ultimate purpose.

The instructor may then decide to re-pose the same question and see whether and how students’ responses have changed. Alternatively, she may present related questions that extend a concept, highlight a distinction, or otherwise build on the prior question. She may explain how the ideas just discussed fit into a high-level picture of the subject. She may summarize key points, helping students to distill what they’ve learned and take notes.

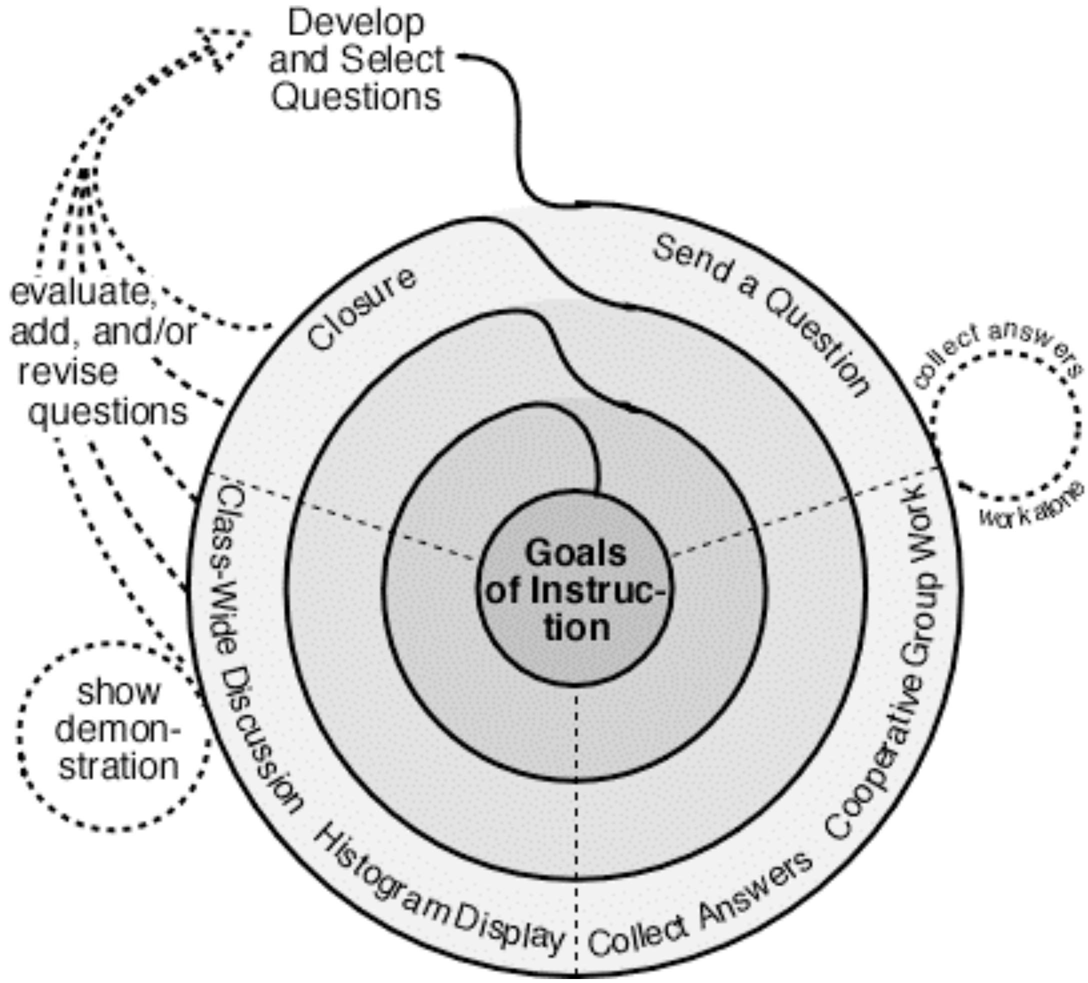

Figure 2: The "question cycle," a design pattern for QDI classes (Dufresne *et al.*, 1996).

Or, she may deliver a micro-lecture on some point of subject matter or problem-solving practice that seems necessary. She can draw on detailed information about students' thinking to make this decision, and the class is well primed to receive the message, appreciate its relevance, and integrate it with other knowledge.

We find that iterating through this cycle of question, group discussion, answering, moderated class-wide discussion and wrap-up three or four times in a 50-minute class is optimal. A higher rate leads to rapid-fire quizzing and loses most of the approach's benefits. Our objective is to have students ponder and discuss, not just answer, and sufficient time must be allowed for full engagement to occur.

Instructor flexibility is important. Some questions will prove surprisingly easy to students and merit little discussion or follow-up, while others will raise unanticipated issues that deserve extra time. Such uncertainty is not a drawback of the approach, but forms the very essence of "agile teaching": genuine discovery of and spontaneous adjustment to students' pedagogic needs.

The question-cycle methodology focuses on helping students explore, sort out, and come to a deep understanding of subject matter, and provides little time for initial presentation of the material to be explored. Instead, students are exposed to and work with material before and after coming to class, via textbook reading, multimedia resources, homework assignments, and other activities. They should appreciate that they are not expected to fully comprehend the material while reading it, but rather to begin the process of making sense that will continue during class and in follow-up homework assignments. This exposure phase is only one loop in the multi-pass learning spiral.

An Exam

"Assessment drives instruction" is an oft-heard phrase in educational reform circles. A QDI approach targeting deep conceptual understanding, reasoning skills, and transferable knowledge will fail if undermined by traditional exams that emphasize answers (product) over reasoning and analysis (process) by testing information recall and high-speed performance on recognized problem types.

Superficially, a QDI-compatible exam may resemble a more traditional one. It may even be a machine-graded multiple-choice test. However, many of the questions contained will target conceptual understanding, reasoning, and transfer. For example, a multiple-choice question may direct students to "Select which of the following principles would be most useful in solving the following problem," or to "Indicate which of the following statements about the given situation are true." Most problems to solve are conceptually subtle rather than computationally complex. In addition, QDI-friendly exams are likely to include innovative or unusual aspects such as a collaborative group component (Cohen & Henle, 1995) or "select all that apply" marking (Leonard, 2005).

HOW DOES ONE PRACTICE *QUESTION DRIVEN INSTRUCTION*?

QDI requires a very different array of skills than does traditional, ballistic, transmissionist instruction. In addition to the obvious technical skills for operating an ARS, an instructor must set appropriate pedagogic goals; design formative assessment items for in-class use; manage a dynamic and highly interactive classroom environment; probe and model students' learning; make instant decisions based on this evolving model; and guide students as they grow into their roles as active learners.

Strategic Decisions: Setting Instructional Goals

From the QDI perspective, instructional goals are viewed as statements about what we want students to *learn*, rather than about what material we intend to *cover*. The distinction between "this course will cover orbital motion" and "this course will teach students to understand and reason with the principles underlying orbital motion" may be subtle, but it is crucial. At the very least, it highlights the absurdity of marching ahead to cover a prescribed syllabus of topics when formative assessments indicate that students aren't getting it. We want to keep the students, not the curriculum, at the center.

To foster active learning, we must think of ourselves as engineers of learning experiences rather than presenters of knowledge. When setting instructional goals and translating them into learning experiences, we should explicitly target mental behavior and skills as well as subject content. Bloom's "Taxonomy of the Cognitive Domain"

(Anderson & Krathwohl, 2001; Bloom *et al.*, 1956) can be suggestive, but is overly general for this purpose. We find it helpful to itemize twelve *habits of mind* that students should seek to develop and teachers should seek to inculcate (Dufresne *et al.*, 2000). The successful practice of these habits of mind, integrated with content knowledge, is the essence of expert-like behavior in science. The twelve habits of mind are:

- seek alternative representations;
- compare and contrast;
- explain, describe, and depict;
- predict and observe;
- extend the context;
- monitor and refine communication;
- generate multiple solutions;
- categorize and classify;
- discuss, summarize, and model;
- plan, justify, and strategize;
- reflect and evaluate; and
- meta-communicate.

These habits of mind can be folded into the curriculum by thinking of them as "what we ask students to do" and the subject matter as "what we ask them to do it with." For example, rather than viewing a question or problem (exam, homework, or in-class formative assessment) merely as a fact for them to recall or a result for them to calculate, we can ask them to:

- Construct a graphical representation of a relationship described algebraically or in words;
- Compare and contrast two processes or situations;
- Describe the behavior of an evolving system;
- Predict the effects of changing one parameter of a system;
- Solve a problem twice, with different approaches;
- Classify a set of situations according to some criterion;
- Describe a strategy for solving a problem without actually solving it; or
- Write an essay summarizing the most valuable things they learned during the course, and what they wish they'd known at the outset.

We also can and should demonstrate these habits of mind for students as we teach, showing them how an expert in the field thinks.

In accord with the principle of multi-pass learning, we should resist treating a course's curriculum as a linear syllabus. Rather, we need to think of it as a complex structure of interconnected, organized ideas and skills that we guide students through, visiting and revisiting sections in various ways as they become conversant with both the global organization and the structural details.

Designing Questions

The criteria for an effective QDI question are quite different from those for exam, quiz, and homework questions, and questions for formative assessment use should be engineered with great care. Elsewhere, we detail a theoretical framework for designing questions (Beatty *et al.*, submitted). In this section we present some general principles and suggestions.

Every question should serve an explicit pedagogic purpose: a specific activity to induce in students' minds, not just a piece of topic mater to cover. For example:

- Drawing out students' background knowledge and beliefs on a topic;
- Making students aware of their own and others' perceptions and interpretations of a situation;
- Discovering particular confusions, misconceptions, and knowledge gaps;
- Distinguishing similar concepts;
- Realizing connections or similarities between different concepts;
- Elaborating the understanding of a concept; and
- Exploring the implications of an idea in a new or extended context.

Computational or simple factual questions, and those that probe memory rather than understanding and reasoning, are of little value. Questions that have students compare two situations, or make predictions and explore causal relationships, are particularly powerful. Good questions push students to reason qualitatively and draw conclusions from a conceptual model. If an instructor can anticipate likely misunderstandings and points of confusion, she should design questions to "catch" students in those, get them articulated, and resolve them through discussion.

Unlike exam questions, ARS questions for QDI benefit from ambiguity. An ambiguous feature sensitizes students to the feature's importance and implications, teaches them to pay attention to subtleties, and motivates discussion of what aspects of a question are important and how they matter. In this way, students can be led to contemplate not just one question but a family of related questions. Similarly, including irrelevant information or omitting necessary information can be beneficial, helping students learn to evaluate what information an answer requires. Questions need not be "fair" or even well defined, since we seek not to evaluate students but rather to help them learn to reason, think defensively, and answer future questions — especially the vague, fuzzy kind often encountered outside the classroom. (However, some questions should be straightforward and provide students with confirmation that they do in fact "get" a particular topic: this is useful feedback to them, and also good psychology.)

A question that elicits a spectrum of answers is generally more productive than one all students agree upon: it provides fodder for discussion and disagreement, leading to engagement and learning.

When designing sets of related or sequential questions, instructors should remember that students experience significant "cognitive load" when reading and interpreting a new scenario. Reusing a situation for multiple questions is efficient, allowing students to concentrate on the relevant aspects of the question at hand and realize the implications of features that do change. Conversely, asking questions with the same conceptual content set in completely different circumstances helps students learn to see through a situation's "surface features" to its "deep structure," and to distinguish the core principles from the details.

When and how a question is presented can shape the depth, quality, and character of resulting student thought and interaction. Students tend to assume that the question relates to whatever has recently transpired in the course, and will apply knowledge accordingly. This can lead to "pigeonhole" learning in which concepts are assimilated chronologically and only accessible within a narrow context, rather than being organized into an interlinked, versatile hierarchy. A careful instructor will mix questions of varying types and topics, and include integrative questions that connect recent ideas with earlier ones.

Classroom Management

Perhaps the most initially daunting (and ultimately exhilarating) aspect of QDI is the necessity of giving up control of the classroom. A lecture is predictable and controlled, with attention safely focused on the instructor. QDI, however, necessarily turns the classroom over to students for dialogue and debate. We must learn to manage the apparent chaos rather than attempting to rigidly control it. Furthermore, the principle of "agility" means we must be prepared — even eager — to modify or discard a lesson plan and extemporize.

Some basic attention-management techniques help considerably. For example, one challenge is to recapture students' attention after they have been discussing a formative assessment question among themselves. An ARS helps dramatically here: by collecting answers (with a time limit) and projecting the resulting histogram on a large screen, attention is redirected to the front of the classroom. Students are naturally curious about each other's answers. Another challenge we face is determining how much time to allow students for small-group discussion of a formative assessment question. Noise level is a clue: when a question is shown, the class is initially quiet as students read and digest it; the noise level then rises as they discuss the question, and begins to fall as they reach resolution. This is an appropriate time to collect answers, display the histogram, and begin the whole-class discussion.

Encouraging students to speak up during the whole-class discussion is crucial. When soliciting volunteers to argue for various answers, we should maintain a strict poker face and not divulge which answer (or answers) is (or are) correct (if any). Allow the students to challenge each other's arguments. If nobody will defend a particular position, ask if anyone else will speculate on the reasoning that might lead to such an answer. (Nothing motivates a student to speak up like having someone else misrepresent his position.) Paraphrasing a student's statements can be valuable, perhaps even necessary in an acoustically challenging room, but we must be careful to stay as close as possible to the student's vocabulary and check with the student that the paraphrase is satisfactory.

When we decide to drop our poker-face and offer a little illumination of our own, we should downplay notions of "correct" and "incorrect" lest we focus students' attention too much on getting the right answers rather than on reasoning and understanding. Instead of commenting that a particular answer or argument is wrong, we can often say “that would be correct *if*…”, indicating some similar situation or question for which it would be valid. This is not only less disconfirming to the student and less deterring to others, it is also more pedagogically productive for all the reasons that “compare and contrast” questions are powerful. We have found that often, students who appear to be offering a wrong answer are instead offering the right answer to the wrong question. Unless they are sensitized to this, telling them they are simply incorrect is confusing rather than enlightening.

Moderating a whole-class discussion presents us with the great danger of making the class instructor-centered rather than student-centered. Working from within students’ perceptions and arguments, rather than making assertions from authority, helps to avoid this. Similarly, if a question contains ambiguities or errors, allowing students to discover these or drawing them out during discussion is preferable to announcing corrections as the question is presented. We should strongly resist any temptation to read a presented question out loud or to talk while students are engaged in small-group dialogue and answering. If we seek active learning, we must give them space to do it!

Tactical Decisions: Modeling Students’ Needs

Though managing the classroom may be the most daunting aspect of QDI, modeling a class-full of students and deciding how best to interact with them is the most enduringly difficult aspect, and it is the very heart of the approach. It requires two distinct skills: modeling and interacting with an individual student, and handling an ensemble of individuals in parallel. Neither comes easily, and both can be truly mastered only by repeatedly trying, occasionally missing the mark, reflecting, and trying again. However, we offer some general advice to help the interested instructor get started.

Interacting “agilely” with a student is a modeling process closely analogous to the scientific method: observe, form a model, make a prediction based on the model, test the prediction, refine the model, and iterate (Gerace, 1992). In this context, we want to model both the student’s knowledge (especially the gaps) and her thinking processes (especially the weaker skills). In contrast to a traditional lecture, we must practice “active listening”: listening carefully and patiently to what she says and how her responses, questions, and other behaviors vary from what we expect. Even when we think we know what she is in the process of asking, we should let her finish: both out of respect and because every nuance of her utterance is valuable data. We will often answer a question with a question, not just rhetorically but to understand better why the student needs to ask hers. Our goal is not to answer her question, but to understand why she needs to ask it.

Rather than concentrating on the knowledge we wish to communicate, a less direct approach is often more effective: trying to figure out what prevents her from understanding, and then attacking the obstacles. This sleuthing out of the roots of confusion is an iterative and thoughtful process on our part. Of course, a rich knowledge of pedagogic theory and common points of confusion are useful. If we find ourselves stumped trying to help an individual, other students in the class can assist. They can often understand their peers better than we.

Clearly, carrying out such an attention-demanding, thorough process with every student in a full-sized class is impossible. We must try to track an array of typical or likely student mentalities, test the class for the accuracy of this array, and teach to it. For example, if a formative assessment question elicits a range of answers, we can ascribe a putative explanation to each one for why a student might select it, and that becomes our working model. Since we have probably prepared the answer set in advance, we should already have ideas about why each answer might be chosen. The distribution of class answers "fits" the model to the class.

This approach does not attach a model to any specific individual in the class. A complementary approach is to identify certain students as representatives of various sub-populations within the class, and then build and maintain as rich a model as possible of each. This can be very powerful: it is easier for us to think in detail about a real, specific individual than an abstract entity, and yet students generally have enough in common that by addressing one student's needs, we impact many. As a side benefit, the more we treat students as three-dimensional individuals, pay real attention to them, and try to understand their thinking, the more they will believe we care about them personally and are "on their side," and the less adversarial the instructional dynamic will be.

Coaching

QDI requires students to adopt a role they might not be accustomed to from more traditional instruction. Our experience is that the vast majority of students express positive feelings about ARS use and QDI after they have adjusted to it, but this adjustment takes time, and some initially greet it with fear and resentment. Students habituated to success under traditional instruction are most likely to be hostile: they have "mastered the game," and now the rules are being changed. Others object out of simple laziness: they are being asked to engage in thought and activity during class, and that is effortful and at times frustrating. They are also expected to complete assignments beforehand so as to be prepared for class. Many are uncomfortable with the idea that they are accountable for material not directly presented in lecture. Inducing students to become participating, invested learners is vital to the success of QDI, and meta-communication is our most powerful tool for achieving that. We can explain to students why we are doing what we are doing, at both the immediate and strategic levels, and how students will benefit. We can talk frankly about the obstacles students will likely encounter and how they can most effectively surmount them. In other words, we can explicitly address learning and communication as part of the "course material."

Some student perceptions merit particular attention. Initially, students will probably view formative assessment questions as mini-tests to be passed or failed. If this attitude is allowed to persist, it will sour them on the formative assessment approach and prevent them from fully and constructively engaging in the process. We must explicitly discuss the purpose of formative assessment and stress that the point is not to answer correctly, but to discover previously unnoticed aspects of the subject and of their own understanding. We must consistently reinforce this position by deemphasizing the correctness of answers and emphasizing reasoning and alternative interpretations. Assigning course credit for "correct" answers is massively counterproductive.

Another perception many students have is that problems are solved quickly or not at all: either they "know" how to do the problem, or they don't. The notion that problems may require protracted cogitation and discussion to figure out, and that these efforts are inherently worthwhile, is alien. They must be convinced of this also before they will lose their resistance to active learning. Again, explicit communication helps.

In general, there is nothing about the course or its content, methods, and objectives that is inappropriate to discuss openly with students. Perhaps "Introductory Physics" and "Cellular Biology" are less accurate titles than "Learning Introductory Physics" or "Understanding Cellular Biology."

CONCLUSION

An audience response system is a powerful tool, but it is only a tool. To make the best use of one, an instructor needs a coherent, comprehensive pedagogic framework that indicates what ends ARS use should serve and how it can be employed to achieve them. Question Driven Instruction is such a framework. It is radical, in that it advocates making an ARS-mediated "question cycle" the core of classroom activity, rather than augmenting traditional instruction with occasional or periodic ARS use.

We know — from personal experience and from assisting others — that mastering QDI is hard and takes time. In our experience, about three years of sustained effort is required for an instructor to really feel comfortable with the approach. However, we also know that it can be mastered, and that the journey and result are transformative for both instructor and students. The change goes deeper than the simple matter of what occupies classroom time: feedback gained about student learning, and the rethinking of pedagogic beliefs this leads to, can impact a teacher's very "way of being a teacher" (Feldman & Capobianco, 2003).

To an instructor beginning to explore ARS-based teaching or looking to get more out of it, the best advice we can offer is to get support. First, try to arrange for mentoring from someone experienced in response system use. Sit in on her classes, and ask her to sit in on yours. You may develop your own style and perspective, but the feedback and ideas will be stimulating. Second, if you can find others also interested in developing their response system pedagogy, form a peer support group to help each other learn through practice, experimentation, discussion, and reflection. One of the great benefits of formative assessment is that the data provide a wealth of feedback about student learning and the effectiveness of pedagogic techniques: feedback that can power ongoing professional development. For this reason, we remind ourselves that we enter the classroom as much to learn as to teach.

Teaching the QDI way, with a response system, can be addictive. Every class is different, surprises abound, and genuine interaction is *fun* for the students and for the instructor.

REFERENCES

Anderson, L. W., & Krathwohl, D. (Eds.). (2001). A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives. New York: Longman.

Beatty, I. D. (2000). Assessing-to-Learn Project Website. <http://A2L.physics.umass.edu>.

Beatty, I. D. (2004). Transforming student learning with classroom communication systems (Research Bulletin No. ERB0403): Educause Center for Applied Research.

Beatty, I. D., Gerace, W. J., Leonard, W. J., & Dufresne, R. J. (submitted). Designing effective questions for classroom response system teaching. American Journal of Physics.

Bell, B., & Cowie, B. (2001). The Characteristics of Formative Assessment in Science Education. Science Education, 85(5), 536-553.

Black, P., & Wiliam, D. (1988a). Assessment and classroom learning. Assessment in Education: Principles, Policy & Practice, 5(1), 7-71.

Black, P., & Wiliam, D. (1988b). Inside the black box: Raising standards through classroom assessment. Phi Delta Kappan, 80(2), 139-148.

Bloom, B., Englehart, M., Furst, E., Hill, W., & Krathwohl, D. (1956). Taxonomy of educational objectives: The classification of educational goals. Handbook I: Cognitive domain. New York: Longmans, Green.

Bonwell, C. C., & Eison, J. A. (1991). Active learning: Creating excitement in the classroom (No. ASHE-ERIC Higher Education Report No. 1). Washington, D.C.: ERIC Clearinghouse on Higher Education, The George Washington University.

Boston, C. (2002). The concept of formative assessment (No. ED470206). College Park, MD: ERIC Clearninghouse on Assessment and Evaluation.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (1999). How People Learn: Brain, Mind, Experience, and School. Washington, D.C.: National Academy Press.

Cheek, D. W. (1992). Thinking Constructively about Science, Technology, and Society Education. Albany, NY: State University of New York Press.

Cohen, D., & Henle, J. (1995). The Pyramid Exam. UME Trends(July), 2, 15.

Dufresne, R. J., & Gerace, W. J. (2004). Assessing-to-Learn: Formative assessment in physics instruction. The Physics Teacher, 42(6), 109-116.

Dufresne, R. J., Gerace, W. J., Leonard, W. J., & Beatty, I. D. (2002a). Assessing-to-Learn (A2L): Reflective formative assessment using a classroom communication system. Paper presented at the Pathways to Change: An International Conference on Transforming Math and Science Education in the K16 Curriculum, Crystal City, Arlington, VA.

Dufresne, R. J., Gerace, W. J., Leonard, W. J., & Mestre, J. P. (2001a). Creating an item for in-class formative assessment. The Interactive Classroom, 1.

Dufresne, R. J., Gerace, W. J., Leonard, W. J., Mestre, J. P., & Wenk, L. (1996). Classtalk: A classroom communication system for active learning. Journal of Computing in Higher Education, 7, 3-47.

Dufresne, R. J., Gerace, W. J., Mestre, J. P., & Leonard, W. J. (2000). ASK-IT/A2L: Assessing student knowledge with instructional technology (technical report No. UMPERG-2000-09). Amherst: University of Massachusetts Physics Education Research Group.

Dufresne, R. J., Gerace, W. J., Mestre, J. P., & Leonard, W. J. (2001b). Assessing to Learn (A2L): Research on teacher implementation of continuous formative assessment. Paper presented at the Winter Meeting of the American Association of Physics Teachers, San Diego, CA.

Dufresne, R. J., Leonard, W. J., & Gerace, W. J. (1992). Research-based materials for developing a conceptual approach to science. Paper presented at the Workshop on Research in Science and Mathematics Education, Cathedral Peak, South Africa.

Dufresne, R. J., Leonard, W. J., & Gerace, W. J. (2002b). Making sense of students' answers to multiple-choice questions. The Physics Teacher, 40(3), 174-180.

eInstruction. (2005). Who's using CPS? Retrieved Jan 24, 2005, <http://www.einstruction.com>.

Feldman, A., & Capobianco, B. (2003, April). Real-time formative assessment: A study of teachers' use of an electronic response system to facilitate serious discussion about physics concepts. Paper presented at the Annual Meeting of the American Educational Research Association, Chicago, IL.

Fosnot, C. (1993). Rethinking science education: A defense of Piagetian constructivism. Journal of Research in Science Teaching, 30(9), 1189-1202.

Gerace, W. J. (1992). Contributions from cognitive research to mathematics and science education. Paper presented at the Workshop on Research in Science and Mathematics Education, Cathedral Peak, South Africa.

Gerace, W. J., Leonard, W. J., Dufresne, R. J., & Mestre, J. P. (1997). Concept-based problem solving: Combining educational research results and practical experience to create a framework for learning physics and to derive effective classroom practices (No. UMPERG-1997-09). Amherst: University of Massachusetts Physics Education Research Group.

Gerace, W. J., Mestre, J. P., Leonard, W. J., & Dufresne, R. J. (2000). Assessing to Learn (A2L): Formative assessment for high-school physics. Paper presented at the Winter Meeting of the American Association of Physics Teachers, Kissimmee, FL.

Hake, R. (1998). Interactive-engagement vs. traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. American Journal of Physics, 66(1), 64-74.

Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. The Physics Teacher, 30(March), 159-166.

Hobson, E. H. (1997). Formative Assessment: An Annotated Bibliography. Clearing House, 71(2), 123-125.

Laws, P. W. (1997). Millikan Lecture 1996: Promoting active learning based on physics education research in introductory physics courses. American Journal of Physics, 65(1), 14-21.

Leonard, W. J. (2005). Every Decision Counts for Better Assessment. Retrieved May 26, 2005, <http://kb.physics.umass.edu/edc>.

Leonard, W. J., Gerace, W. J., & Dufresne, R. J. (2001). Questions First (Q1st): The challenges, benefits, drawbacks, and results of asking students questions prior to formal instruction. In S. Franklin, J. Marx & K. Cummings (Eds.), Proceedings of the 2001 Physics Education Research Conference (pp. 41-44). Rochester, NY: Rochester Institute of Technology.

Leonard, W. J., Gerace, W. J., Dufresne, R. J., & Mestre, J. P. (1999). Concept-Based Problem Solving. In W. J. Leonard, R. J. Dufresne, W. J. Gerace & J. P. Mestre (Eds.), Teacher's Guide to Accompany "Minds*On Physics: Motion". Dubuque, Iowa: Kendall/Hunt.

Mazur, E. (1997). Peer Instruction: A User's Manual. Upper Saddle River, NJ: Prentice Hall.

McDermott, L. (1991). Millikan Lecture 1990: What we teach and what is learned — Closing the gap. American Journal of Physics, 59, 301-315.

McDermott, L. (1993). Guest comment: How we teach and how students learn — a mismatch? American Journal of Physics, 61, 295-298.

Mestre, J. P. (1991). Learning and instruction in pre-college physical science. Physics Today, 44(9), 56-62.

Mestre, J. P. (1994). Cognitive aspects of learning and teaching science. In S. J. Fitzsimmons & L. C. Kerpelman (Eds.), Teacher Enhancement for Elementary and Secondary Science and Mathematics: Status, Issues and Problems (NSF 94-80) (pp. 3.1-3.53). Washington, DC: National Science Foundation.

Mestre, J. P., Dufresne, R. J., Gerace, W. J., & Leonard, W. J. (2001). The multidimensionality of assessing for understanding. Paper presented at the Winter Meeting of the American Association of Physics Teachers, San Diego, CA.

Milner-Bolotin, M. (2004). Tips for Using a Peer Response System in a Large Introductory Physics Class. The Physics Teacher, 42(4), 253-254.

O'Loughlin, M. (1993). Some further questions for Piagetian constructivists: A reply to Fosnot. Journal of Research in Science Teaching, 30(9), 1203-1207.

Penuel, W. R., Roschelle, J., Crawford, V., Shechtman, N., & Abrahamson, L. A. (2004). Workshop report: Advancing research on the transformative potential of interactive pedagogies and classroom networks. Menlo Park, CA: SRI International.

Redish, E. F., & Steinberg, R. (1999). Teaching physics: Figuring out what works. Physics Today, 52, 24-30.

Roschelle, J. (2003). Keynote paper: Unlocking the learning value of wireless mobile devices. Journal of Computer Assisted Learning, 19, 260-272.

Roschelle, J., Abrahamson, L. A., & Penuel, W. R. (2004, April 16). Integrating classroom network technology and learning theory to improve classroom science learning: A literature synthesis. Paper presented at the Annual Meeting of the American Educational Research Association, San Diego, CA.

von Glasersfeld, E. (1991). A constructivist's view of learning and teaching. In R. Duit, F. Goldberg & H. Niedderer (Eds.), Research in Physics Learning: Theoretical Issues and Empirical Studies: Proceedings of an International Workshop. Kiel, Germany: Institute for Science Education at the University of Kiel.

von Glasersfeld, E. (1992). Questions and answers about radical constructivism. In M. Pearsall (Ed.), Scope, Sequence, and Coordination of Secondary School Science, Volume II: Relevant Research (pp. 169-182). Washington, DC: National Science Teachers Association.

von Glasersfeld, E. (1998). Cognition, construction of knowledge, and teaching. In M. R. Matthews (Ed.), Constructivism in Science Education. Dordrecht, Germany: Kluwer.