There is a mismatch between the goals of science education — a deep understanding of science concepts, the ability to apply science knowledge to solve problems, and an appreciation that science is a process of inquiry — and the way we assess student progress toward these goals—periodic cumulative exams that test for information and low level problem-solving skill. Such cumulative exams lead to rote learning on the part of students and cannot be used by teachers to shape instruction in a continuous and dynamic fashion. We advocate an alternative approach that we refer to as Assessing-to-Learn (A2L). The A2L approach attempts to integrate reflective formative assessment (RFA) and instruction in a way that is consistent with constructivist and active learning pedagogy. RFA uses classroom communication technology to gather and display student responses to questions posed during class. The immediate and anonymous summary of student responses furnished by a classroom communication system (CCS) provides teachers and students with useful and timely information about students’ understandings and ways of reasoning. RFA also helps to create an active classroom environment by stimulating student participation and class discussion. At the same time, RFA gives teachers useful information for making real-time teaching decisions. RFA represents a powerful mechanism for encouraging student self-awareness of their thinking and learning habits. A description of the A2L philosophy and pedagogy are included here along with some examples of RFA questions in the domain of physics.

Overview of the Assessing-to-Learn Approach

We are engaged in the development of formative assessment materials (assessment materials that the teacher uses to make decisions about subsequent instruction) for use with high school college level physics curricula. These materials are being designed with the specific goal of fully integrating assessment and instruction, and are intended for use with a CCS. A CCS permits teachers and students to get immediate feedback in the form of histograms displaying the class’ responses to questions. Integrating assessment materials with a teacher’s existing curriculum enables the teacher to assess students’ progress and performance (on individual or small-group activities) while students simultaneously engage in pedagogically sound learning activities. This form of ongoing assessment empowers teachers to determine firsthand, and in a continuous fashion, the effectiveness (or ineffectiveness) of their own curriculum materials and instructional approach, thus providing a powerful impetus for teacher change.
Successful implementation of the A2L approach depends upon a number of factors:

- The A2L approach requires a large, comprehensive set of assessment items to serve as exemplars for teachers. The items must be designed to have instructional value and must address a range of cognitive capacities: conceptual understanding, reasoning, analysis, knowledge-organization and problem-solving skills. A2L activities should be consistent with constructivist and active-learning pedagogies. Assessment items should be designed to reveal information needed to guide instruction.

- To facilitate a teacher’s transition to using RFA, assessment items should be accompanied by support materials (or teacher’s guide). Such a guide would have answers to the assessment items and relevant background information. At a minimum it should contain the following information: (a) a discussion of the purpose, (b) suggestions for classroom implementation, (c) pertinent research on student misunderstandings, and (d) effective instructional strategies to help students grasp the targeted concepts or procedures.

- Although the aim of A2L materials is to facilitate teachers’ ongoing formative assessment, the items need to be specifically designed to serve as quality-learning experiences for students. A2L items should target the cognitive difficulties identified by science education research and employ a variety of techniques, such as having students use multiple representations, work in cooperative groups, and carry out hands-on activities. The assessment activities should lead to a more student-centered and interactive learning environment to be consistent with the overall goals of A2L.

- Ongoing assessment has the potential to provide teachers with valuable information on students’ understanding. We conjecture that feedback obtained when teachers probe students’ understanding on a continuing basis will result in a more responsive instructional style and make teachers receptive to the adoption of alternative pedagogical strategies. What types of support teachers need to make changes remains an open question.

Assessing-to-Learn Components

The A2L approach is composed of four components: an overarching pedagogical perspective, effective use of technology, carefully crafted formative assessment items, and informative instructional support materials.

PEDAGOGICAL PERSPECTIVE

A2L pedagogy is consonant with constructivist epistemology, which asserts that individuals actively construct the knowledge they possess. The construction of knowledge is often an effortful process requiring significant mental engagement by the learner, and taking place within a context of social interaction and agreement [1] [2]. What individuals learn is greatly influenced by the knowledge they already possess. If new knowledge conflicts with resident knowledge, the new knowledge will not make sense to the learner and may be constructed in ways that are not useful for long-term recall or for application in problem-solving contexts [3] [4] [5] [6] [7]. From a constructivist view of learning, instruction should be crafted to provide students with fertile opportunities to confront and assess their current knowledge and understanding. This can only be effectively accomplished within the classroom by adopting active learning strategies, including cooperative learning and problem-based learning. Within the A2L approach, teachers employ
cooperative learning groups and use the assessment items as a focus of group activities and discussions. Teachers also conduct class-wide discussions to elicit student reasoning, and to ask students to evaluate their own and others’ reasoning.

The A2L approach adopts the view that the role of teacher is one of coach, rather than dispenser of information. Good coaching requires reliable two-way communication between the coach and the student. RFA is intended to facilitate communication in the classroom. To this end, A2L items should allow the teacher to diagnose preconceptions, which have been found to be pervasive and resistant to change (for reviews, see [12] [13] [14]). Other items should probe other known areas of student difficulty [15] [16] [17] [18] [19] [12] [13] [20] [21].

THE ROLE OF TECHNOLOGY

Implementation of continuous assessment faces a number of challenges: (a) the loss of class time devoted to assessment, (b) information gleaned from assessment is not timely enough to impact instruction, and (c) the clerical nightmare that useful record keeping presents to teachers. A CCS can help remove these obstacles. CCSs provide an integrated package that permits: 1) presentation of questions to the class, 2) collection and storage of individual student answers, 3) anonymous display of a histogram of the class’ responses, and 4) an ongoing permanent record of each students’ progress. As with any technological advance, new opportunities have associated dangers. It is important that teachers come to see the technology as a powerful instructional tool that improves communication. Used merely as an efficient way of grading students, technology diminishes, rather than enhances, the learning environment.

The A2L instructional approach consists of having students engage in learning activities or problem solving tasks related to a question presented to them via a CCS. Depending on the situation, students work individually or in groups of 2-4. After an appropriate amount of time, students enter a response to the question. The answers are passed along to a computer at the front of the room. CCS software then generates a histogram that the instructor displays to the class. Viewing the distribution of answers reinforces the fact that there is disagreement, which in turn stimulates student interest. The display of the histogram is a powerful tool for initiating class-wide discussions of the ideas and methods used to analyze situations and solve problems. In a class-wide discussion, some students volunteer their reasoning, with other students offering rebuttals or amplifications. The instructor moderates the discussion and ensures that closure is reached. Generally, the class is conducted more like a workshop than a lecture. The time devoted to lecturing is decreased, while the time students devote to developing and refining their conceptual understanding is increased. With the feedback on students’ understanding provided by the RFA process, the focus of instruction is toward uncovering material, rather than covering it.

Our experiences lead us to believe that technology presents a powerful solution to the challenges facing formative assessment in a high school setting.

(a) Class time lost to assessment activities are more than compensated by
• increasing the number of active learning experiences in science classes.
• making class time more enjoyable, and therefore more motivating, to students.
• making assessment activities genuine learning experiences for students.
• providing a more equitable learning experience to a diverse student population.
Immediate feedback on the results of instruction and activities can help:
- teachers become more aware of what their students can and cannot do.
- teachers become more aware of their own communication skills.
- students become more confident and outspoken when they realize their views are shared by other students.
- both students and teachers become aware of the value and importance of formative assessment.

THE ROLE OF ASSESSMENT MATERIALS

Assessment materials that are to serve a formative function must not look like end-of-chapter problems, or like typical quantitative questions appearing in traditional multiple-choice tests. Those types of questions have a known undesirable byproduct: they engender in students the inclination towards memorization and equation manipulation. This style of assessment and the associated learning liabilities stem from the perspective that assessment primarily serves as a mechanism for evaluating or ranking students.

For use in RFA, assessment materials must meet the following criteria:

- **promote learning rather than grade students’ performance.** RFA requires that students’ thinking be made explicit so that teachers and students can work together toward the common goals of developing conceptual understanding and problem-solving skills. The materials will succeed only if students get the message: *answer questions in terms of how you think—not what you believe your teachers want to hear.*

- **help students apply concepts flexibly across a wide range of problem contexts.** Research indicates that beginning physics students do not build a self-consistent knowledge base, but rather store in memory pieces of unrelated knowledge that are not linked to contexts of applicability [23] [24]. The materials must help students build strategic knowledge elements, that is, tie concepts and principles to the contexts where they can be applied and to the procedures that are needed to apply them.

- **provide teachers with an independent assessment of students’ understanding.** To be useful to teachers, assessment materials must cover a wide range of topics. Simultaneously they must provide teachers with an independent measure of concept understanding and problem-solving skill deemed important by state and national science standards. In our work with teachers, many tell us that they would like assessments that probe for deep conceptual understanding but are frustrated at the lack of time or expertise to develop them.

- **generate rich inter-group, as well as class-wide discussions.** Few students learn well in isolation. Questions need to be designed to highlight major concepts and problem-solving procedures as a context for small group and class-wide discussion.

ROLE OF INSTRUCTIONAL SUPPORT

By themselves, formative assessment items are not enough. Accompanying support materials are needed to help teachers with implementation issues. Teacher aids can serve to assist teachers in designing their own instructional interventions for students. We have identified four potentially useful pieces of information for teachers: 1) an explanation of the underlying purpose/significance of the item, 2) a discussion of the item and responses, 3) interpretations of the answers commonly given by students, and 4) insights into student reasoning gleaned from research.
It may also be useful to provide teachers with suggested instructional strategies. For example, “bridging analogies,” which attempt to bridge from correct anchoring intuitions that students possess toward a target situation where the student possesses deeply rooted misconceptions, have shown considerable promise [25] [26]. Another example is the “interactive demonstration,” in which students are asked to make predictions about a demonstration before it is performed by the teacher. These predict-then-show demonstrations focus on concepts that students find very difficult (e.g., Newton’s Third law), and on situations where students’ predictions are not in accord with observation. When students fail to predict the outcome of a demonstration that they believe they understand, they experience cognitive dissonance, which leads to increased curiosity and receptivity on their part. This approach has shown considerable success in helping students permanently overcome persistent misconceptions [21] [27] [28].

Examples of Assessing-to-Learn Items from the Domain of Elementary Physics

In developing A2L items we have found it useful to employ a classification scheme describing different stages of students’ conceptual development within a domain. The classification scheme has five levels: (a) explore, define, and hone concepts, (b) link and cluster concepts, (c) develop analysis and reasoning skills, (d) develop concept-based problem solving skills, and (e) organize, prioritize, and structure knowledge. In what follows we provide some examples and a brief description of the underlying purpose of each type.

**Explore Naive Concepts** — All students come to their physics classes with a tremendous amount of experience and understanding. A great deal of the students’ prior knowledge is in conflict with formal physics concepts and principles. It is important for students to have the opportunity to air their understanding and to hear what other students think. It is equally important for teachers to be aware of students’ pre-instructional understanding so they can better tailor instruction to their students’ needs. Thus, for many topics we create A2L items for use prior to formal instruction on particular concepts.

An example of this type of assessment item is shown in figure 1. In this case the item is a set of six questions. The item addresses the issue of perceiving interactions, and it would be used prior to a formal study of forces. Perceiving interactions is a necessary first step in identifying the forces exerted on an object or system and is fundamental to all of mechanics. An interaction between two objects is usually perceived through the effects the objects have on each other—for example, sometimes the motions of the objects are changed, sometimes the objects’ shapes are changed, sometimes both. Students may perceive interactions when there are changes in the shape of objects, especially when the objects return to their “natural” state when they are no longer interacting (as would be the case for the water balloon and spring in situation A). However, when there is no motion, and neither object is perceptibly deformed, students are less likely to perceive an interaction [26]. (The teacher aid for this item might contain the suggestion that physical situations resembling the situations depicted in the figure be set up so that students may manipulate them.) The pattern of answers for the three situations shown would inform teachers regarding what features students associate with interactions.

**Honing and Clustering** — When students first learn a formal physics concept they do so in a limited context and in isolation from other closely related ideas. Over time the students are expected to generalize their understanding of a concept and integrate it with other knowledge so that they can apply the concept in a wide range of contexts. This rarely happens in most physics
(or science) courses, where problem solving is predominately quantitative. Since students generally have limited mathematical skills, focusing on quantitative problem solving necessarily means that students will only get to consider a narrow set of contexts — those amenable to an elementary mathematical solution. Since a reasonable fraction of students are capable of coping with a small number of contexts by rote learning, the inability of students to apply physics concepts broadly across contexts often remains hidden from the teacher. Only by getting students to use a concept in a large number of contexts, and in relation to other concepts, is it possible to know whether students’ (correct) answers to questions represent real understanding or simply rote learning. Thus A2L items should require students to use and understand concepts across a broad set of contexts and in relationship to other concepts.

Some examples of Honing and Clustering assessment items are shown in figure 2. Figure 2(a) provides an example of how an assessment item can be structured so that students compare and contrast situations involving several concepts (pressure, force, buoyancy, and weight). An important feature of this item is that after students compare, predict and discuss what will happen in each situation they can actually carry out an experiment. In a second example shown in figure 2(b), the student is being asked to relate features of a graphical representation of velocity to a description of a physical situation. Asking students to work with a variety of representations (in addition to the algebraic representation) is a powerful way to explore student thinking. Finally, the item in figure 2(c) is a set of questions that explore students’ understanding of a basic concept (normal force) in a diverse set of situations, some of which are known to elicit misconceptions.

**Analyze and Reason using Concepts** — Once a student understands a concept (or set of concepts), an important goal is to get students to use their understanding to analyze and reason about more complex situations. By analysis we mean “to break down into basic parts to better understand the whole.” Reasoning involves drawing conclusions or making judgments. Although such thinking skills are often cited by high school teachers as a primary goal of their instruction, rarely do students develop such skills. Further, most teachers have no way to determine how well their students can analyze and reason, since traditional problem-solving tasks are not directly sensitive to these skills: For example, over and over again studies have shown that even students who do well on standard physics exams often have only a shallow understanding of basic
concepts and little capacity to use concepts to reason about a problem. Therefore it becomes important to develop A2L items that require students to apply concepts in nontrivial ways to answer questions about physical systems. Some of these items may be open-ended, requiring students to make assumptions and set goals. An important element of the Analyze and Reason assessment items is that students deal with complex situations and questions that can be addressed qualitatively, but would be extremely difficult to solve using an equation-centered approach — in other words the student cannot mindlessly use an equation or mimic some procedure presented by the teacher or textbook.

Figure 3(a) shows one example of an Analyze and Reason assessment item that is more open-ended than some of the previous examples. Students are given a motion (strobe) diagram of a thrown ball showing velocity vectors at each point and are asked to deduce whether air resistance is significant. Students must decide what features of the strobe diagram they should analyze to gain information about air resistance, and they must decide on some criterion for determining whether air resistance is significant. Figure 3(b) contains a second example of an Analyze and Reason item in which students must use an alternate representation. In the example, students are shown four different electric field diagrams. For each diagram a charge undergoes a displacement. Students are asked to determine the situation for which the work done by the field on the charge is zero. Figure 3(c) shows an example where students must compare and contrast the motion of, and the forces exerted on, a set of blocks under three different conditions. Finally, in figure 3(d) students are asked to compare the size of electrical forces.

Figure 2: (a) Comparing scale readings; (b) associating motion with graphs of velocity vs. time; (c) comparing magnitudes of the normal force.
All of the charge configurations below have the same radius and linear charge density (some positive, some negative). For which configuration would the electric field at the origin be greatest in magnitude?

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In each of the situations below, a negative charge is moved along a path from point a to point b in the presence of an electric field. **Question:** For which is the work done on the charge by the field zero?

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In which of the three situations above is the net force on block C the largest?

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Figure 3: (a) Reasoning about forces using Newton’s second law; (b) reasoning about electrical potential energy using field diagrams; (c) analyzing a system of three blocks on a horizontal surface; (d) comparing the size of electrical forces.
Organize and Interrelate Groups of Concepts—Students have great difficulty relating ideas from different parts of a course, and identifying what is truly important from what is not. When students are asked to name the most important ideas covered in their physics course, they tend to focus on minor factual knowledge rather than major concepts and principles [29]. In physics, few students recognize that there is a small set of major principles that can be used to reason about a wide range of physical situations. Even fewer students are capable of determining which concepts can be appropriately used in a given situation, and of judging whether a particular principle could be employed fruitfully to solve a given problem. Some A2L items should require students to work with major concepts and principles from different parts of the course, and should provide opportunities for students to reflect on what are the significant ideas in the course.

Figure 4 presents an item in which students are asked to compare two problems. The item proceeds in three parts. First students would be asked to decide whether they would solve the two problems using a similar approach. For each problem, students would be asked to identify a principle that could be used to solve the problem. After a class discussion of the reasons for students’ choices, students would be asked to repeat the first part but with a different problem pair. The item helps teachers to determine what features of a situation students focus on when making decisions about how to solve a problem. (Students often incorrectly state that the problems are solved similarly since they both involve a body moving down a track.) It also reveals the extent to which students can successfully choose an appropriate principle for solving a given problem, as well as the reasoning that students use in selecting a principle. This item is a good example of how assessment can also serve as a good learning experience. The issues involved in the example (i.e. cueing on the principle that can be used to solve the problem rather than surface features) are rarely if ever raised explicitly with students. Students are left to find the patterns on their own and consequently focus predominately on surface features of problems when trying to decide whether problems would be solved similarly [15] [20]. The relationship between major physics principles and problem solving remains obscure for most students. This assessment item provides students an opportunity to reflect on the role of principles in solving problems.

Concept-Based Problem-Solving — A goal of instruction is to improve students’ ability to use their knowledge of physics concepts to solve both quantitative and qualitative problems. In most traditional courses students focus so much on the algebraic aspects of problem solving, they never learn how to use physics concepts to solve problems. To focus students’ attention on concepts, we have found it necessary to give students activities that explicitly require them to describe and assess how various concepts and principles could be applied to solve a problem. There is a need for items that require students to write and analyze strategies and solution plans that explicitly state how various concepts and principles could be applied to a problem situation.

Figure 5(a) shows an item that helps determine whether students are able to apply Newton’s second law in different contexts. Students find question 1 fairly easy to answer correctly. Taking the system to include both carts, they can determine the net force to be the difference of the two applied forces, and divide by the total mass to get the acceleration. Most will also be able to describe accurately this procedure. Most students are unable to answer question 2 correctly, however, even though this requires only the application of Newton’s second law to cart B (alone) using the acceleration from question 1. Many students abandon the physics they have learned and rely on their intuition. Some students think that the force pulling on A is simply transmitted through the cart, so A pulls on B with 0.5N of force. Others think that the force
**Problem A.** A child on a skateboard is rolling down a ramp having straight and curved portions as shown. What is the speed of the skateboarder when she reaches the end of the ramp (if we ignore the effects of friction and air resistance)?

**Problem B.** A 10kg block is released from rest onto a curved frictionless track from an unknown height \( h \). The block is traveling at 7m/s just before it collides and sticks to a 5kg block. From what height was the block released?

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**Question 1:** Would you solve these two problems using similar approaches? (Answer Y for Yes or N for No.)

**Question 2:** What principle would you use to solve Problem A? (Enter a text string.)

**Question 3:** What principle would you use to solve Problem B? (Enter a text string.)

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**Figure 4:** Organizing physics principles around problem solving.

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Two air carts, each of mass 0.2kg and initially stationary, are attached to each other on an air track. The forces on each cart are shown.

**Question 1:** What is the acceleration of the system? (Enter your answer in m/s\(^2\)).

**Question 2:** What is the force that cart A exerts on cart B?

(A) 0.2N  (E) 0.5N  
(B) 0.3N  (F) 0.8N  
(C) 0.4N  (G) none of the above  
(D) 0.45N  (H) impossible to tell

**Figure 5(a):** Problem solving with Newton’s laws.

between the two carts is the sum, or difference between the two applied forces. Sometimes students select the correct answer (in this case 0.4N) using faulty reasoning or by selecting some random mathematical procedure, such as averaging the two applied forces. (The teacher aids for this item might suggest techniques for probing students’ understanding once the teacher believes that students have grasped the underlying physics. For example, the same situation could be used but with carts of different masses. Finally, this item lends itself nicely to a laboratory exercise.)
Figure 5(b) shows a Concept-based Problem-Solving item in which students are presented with two procedures for solving a given kinematics problem. For each procedure the students are asked to determine whether or not the procedure is valid, and if it is not valid, to identify which of the indicated steps is inappropriate for solving the problem. This type of item can be used to make students (and teachers) aware of common procedural mistakes students make when solving physics problems. For example, students too often over-generalize what they learn and apply a given result in situations where the result is inappropriate. With respect to the problem in figure 5(b), it is quite common for students to use the set of equations derived in kinematics for constant acceleration, even when the acceleration is not constant. Thus many students will think the second procedure is valid even though it is not. (This outcome is all the more likely for the problem shown because only the direction of the acceleration is changing; the magnitude of the acceleration is constant.) This type of item allows both students and teachers to reflect on the process of using their physics knowledge to solve problems. It also addresses issues of scientific literacy. Reading and writing in science often requires skills much different than those required in non-science areas.

**Procedure I:**

(A) Draw a graph of the velocity of the toy car vs. time. (B) The graph starts out at zero and increases to a maximum of \( v \) at \( t = 2s \), then decreases back to zero at \( t = 4s \). (See diagram.) (C) The area below this graph is the displacement of the car, which is 3m. (D) So, equate the area below the graph to 3m, and solve for the unknown speed \( v \). (E) The slope of the velocity vs. time graph is the acceleration.

**Procedure II:**

(A) The acceleration of the toy car is constant and the same for the entire motion of the car. (B) The whole process takes 4 seconds, and the displacement is 3 meters, so use the formula:

\[
\Delta x = v_0 t + \frac{1}{2} a_x t^2
\]

where \( v_0 \) is zero, \( \Delta x \) is 3m, and \( t \) is 4s. (C) The only unknown in the equation is the acceleration \( a_x \), so solve for it.

**Problem:** Your little sister is playing with a toy car. She winds it up and lets it go. The car speeds up at a constant rate for 2s, then slows down at the same rate (also for 2 seconds) until it stops 3 meters away. What was the acceleration of the toy car for the first 2 seconds of its motion?

**Procedure I:**

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\]

where \( v_0 \) is zero, \( \Delta x \) is 3m, and \( t \) is 4s. (C) The only unknown in the equation is the acceleration \( a_x \), so solve for it.

**Question 1:** If Procedure I is invalid indicate the invalid step. Enter V for valid.

**Question 2:** If Procedure II is invalid indicate the invalid step. Enter V for valid.
Habits of Mind

One of the potential benefits of the A2L approach is its emphasis on the two-way communication between teacher and students. By increasing the amount and quality of the communication process, opportunity exists for interacting with students’ existing habits of mind. (By a habit of mind we mean a natural tendency or willingness as applied to mental processes.) We know that students have certain habits of mind that impede their learning. For example, students’ tend to memorize facts and formulas, reduce engagement, and lack self-awareness. Ultimately, we would like to encourage habits of mind that when applied to activities and experiences will lead to critical-thinking skills.

“Basic” Habits of Mind. We believe that certain habits of mind correspond to particular mental processes needed for active engagement and intellectual growth. The first set of these are referred to as “basic” because they are slightly more fundamental than those labeled as “advanced”. They are also more widely applicable, because they can be encouraged during all stages of learning. The basic habits of mind are listed to the right. They will be explained in greater detail later.

“Advanced” Habits of Mind. The “advanced” habits of mind are more easily applied to later stages of learning. However, this does not mean that they are less valuable. In fact, to reach the stage of being a proficient, concept-based problem solver, students must have begun to develop all of these habits of mind. They are listed to the left. These also will be explained in greater detail below.

Beginning students come into our classrooms with a wide variety of ideas about science, about themselves, about instruction, and about learning. Many of these “preconceptions” interfere with learning and inhibit each student’s ability to develop desirable critical-thinking and problem-solving skills. Unless students confront any mismatch between scientific ideas and their own conceptions, they will not understand the concepts and principles on which science is based and will find it difficult to solve science problems outside of a limited context. Unless students develop analysis and reasoning skills, they will continue to use superficial approaches to solving problems. Their problem solving will remain algorithmic and reach barely beyond the level of equation and symbol manipulation. Each of the habits of mind has a role in prompting students to stay actively engaged.

Seek alternative representations. Have students interpret, translate between, and use a variety of representations. A representation can be algebraic, graphical, pictorial, physical, or verbal, just to name a few types. When students have command of many different representations,
they are more likely to use them to communicate ideas (e.g., with classmates) and they are better able to analyze physical situations before solving problems.

**Compare and contrast.** Students should be prompted to look for patterns. When students look for and perceive similarities and differences between situations, they are more likely to distinguish concepts and at a higher level, appreciate the role of principles in analysis and problem solving.

**Explain, describe, draw, etc.** Encourage students to describe their observations and experiences, explain their reasons behind any answers they give, and in general be open to letting others see the inner workings of their minds.

**Predict & Observe.** Students should become aware of their own models of the physical world and test their models by applying them to new situations, defending their predictions, and comparing their predictions with observations. Students cannot easily confront the flaws in their models, become self-aware, or learn unless they are willing to commit to an answer, explain it, and reflect on it.

**Extend the context.** Each of us has a “safety zone” of thought, interaction, and experience, and it can be a little frightening to go outside of this zone. But learning occurs necessarily at the boundary of this safety zone, so students benefit from being willing to consider and analyze unfamiliar situations. Exploring a range of contexts helps to distinguish relevant features from irrelevant ones, and also helps to avoid oversimplified generalizations.

**Monitor and refine communication.** Students need to take greater responsibility for communication, whether between them and their classmates or between them and their teacher.

**Generate multiple solutions.** Students often have only one way of solving a problem or answering a question. And if they are stuck, they usually don’t know how to get themselves unstuck. Even simple problems and questions usually have many valid solutions and explanations, yet students perceive that there is only one “right” way and one “right” answer. Having students solve the same problem in a new way sensitizes them to different approaches and helps them learn new principles and prioritize approaches.

**Categorize and classify.** Looking for patterns, breaking up ideas, situations, or problems into categories, and naming them are useful tendencies, because they can lead to understanding, structured knowledge, and improved memory recall. By exposing students to different classification systems, they learn to distinguish ideas.

**Discuss, summarize, model, etc.** Higher order thinking skills are developed when students discuss, listen, seek clarification, ask questions, summarize, paraphrase, distill, and model. Many students, however, are inclined to “tune out” what their classmates are saying and rely on the teacher to distill the information down to its essential content.

**Plan, justify, and strategize.** A strategy is defined to be a principle chosen to be applied to a problem, a justification of its validity and appropriateness for the particular problem situation and question, and a plan for applying the chosen principle and getting an answer. Forward-looking approaches are highly valued by scientists and teachers of science, but they are seldom encouraged in students.

**Reflect, evaluate, etc.** An essential habit of mind is reflection, along with all of its related higher order thought processes, such as evaluating, integrating ideas, generalizing, etc. Students
must be given time to explicitly reflect on their experiences, as well as time to verbalize their reflections. Most students do not usually appreciate the value of reflective thought.

Meta-communicate. Meta-communication is a term we use to refer to communication about learning. To meta-communicate is to talk about learning styles and outcomes, about concepts and principles and their roles in problem solving, about structuring knowledge and its purpose, about the usefulness of learning physics or math or any other subject, and about how different individuals have different learning approaches.

Final Thoughts
The A2L approach seeks to use RFA to alter the classroom dynamic and to place greater emphasis on development of scientific habits of mind. We advocate frequent use of formative assessment to make the science classroom more interactive and to provide increased opportunities for learning. Formative assessment helps teachers stay informed about their students’ learning and shifts the focus of instruction away from the delivery of content toward helping students to become better learners and to develop higher level process skills.

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