

## Millikan Lecture 1999: The Workplace, Student Minds, and Physics Learning Systems

Alan Van Heuvelen

Citation: *American Journal of Physics* **69**, 1139 (2001); doi: 10.1119/1.1399043

View online: <http://dx.doi.org/10.1119/1.1399043>

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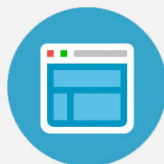
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# Millikan Lecture 1999: The Workplace, Student Minds, and Physics Learning Systems

Alan Van Heuvelen

Department of Physics, Ohio State University, Columbus, Ohio 43210-1106

We review three important ideas concerning physics education. First, what do surveys from the workplace indicate about the relative importance in student education of scientific process knowledge, personal skills, and conceptual physics knowledge? Second, what are the characteristics of student minds that need to acquire this knowledge and these skills? Finally, what can we do with physics learning systems to help these minds better acquire this knowledge and these skills?

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[DOI: 10.1119/1.1399043]

## I. INTRODUCTION

There is a growing consensus from the world outside of education concerning the desired outcomes for that education. There is also a growing understanding of how students' minds work and why they have difficulties learning subjects like physics. In recent years, there have been experiments with new learning systems that indicate that we can do better in helping those minds acquire *some* of the desired outcomes. In this paper we consider these three ideas: the desired outcomes for our education, a very brief look at the student mind, and features of learning systems that help students achieve the desired outcomes.

## II. REPRESENTING THE EDUCATION SYSTEM

We can represent these ideas nicely using a transformer model. A transformer is a device that allows efficient transfer between two objects with different characteristics—different characteristic impedance. For example, the speaker in a high fidelity system is a transformer for converting electrical oscillations into mechanical oscillations of air in front of the speaker. The electrical system is very different from the air. To be an efficient transformer, one side of the speaker should have the same characteristic impedance as the electrical system. The other side of the transformer should have the same characteristic impedance as the air. There should be a smooth transition inside the transformer so that the signal is not reflected at interfaces inside. Designing a good speaker requires considerable understanding of the impedance of the air, the impedance of the electrical system, and care in constructing the speaker's internal components to avoid internal impedance mismatches.

We can use this same model to represent an educational system (Fig. 1). The student mind with its characteristic impedance is considered the load. Conceptual and procedural knowledge that we would like a student to acquire is considered the source. Our goal is to build an education transformer, a learning system, which helps student minds acquire this source material. The learning system transformer includes anything we choose: an instructor, the physical environment of the classroom, other students in the class, various pedagogical strategies, different types of classroom activities, books, CDs, laboratory equipment, the format for the course, and whatever we need to make the learning system transformer match impedance. If either or *both* interfaces are mismatched, as represented schematically in Fig. 2, the edu-

catinal experience is less than optimum—possibly much less.

With this model in mind, we can identify again three important goals for physics education—the subjects of the remainder of this paper. First, we must choose the conceptual knowledge, the process skills, and the personal characteristics that we want students to acquire—the source material. Second, we must determine the characteristic impedance of the student mind. Finally, we need to build an education system that has an impedance match with that mind and with the desired source material. In this article, we focus on these ideas relative to the introductory physics courses for science and engineering students. Many of the ideas are general and apply to other courses in physics.

## III. CHARACTERISTICS OF THE SOURCE—THE DESIRED OUTCOMES FOR OUR INSTRUCTION

Traditionally, the goals for a one quarter or a one semester physics course have been to help students learn the physics concepts in 10 or 15 chapters of a book and to learn to solve the end-of-chapter problems. Are these the best goals? In this section we consider advice from two sources: (1) a study in the 1950s by a committee headed by Benjamin Bloom; and (2) several recent studies concerning the knowledge and skills needed in the workplace.

**Bloom's Taxonomy:** In 1956, Benjamin Bloom and others reported on an effort to assess student learning.<sup>1</sup> Their report identified educational objectives that should be a part of education (see Table I). Their work became known as Bloom's Taxonomy for the Cognitive Domain. The objectives form a hierarchy in which higher-numbered skills depend to some extent on lower-numbered skills—although they often blend together in real practice.

Our traditional education focuses on level 1 (knowledge), a little on what is described for level 2 (comprehension), and a little on what is described for level 3 (application). The latter three higher level skills (analysis, synthesis, and evaluation) seldom receive any attention in our physics instruction—even in higher level courses. Are these objectives important in the practice of real science? Should physics education at all levels place more emphasis on the higher level cognitive skills? Consider carefully the following workplace studies and decide if they are asking for students with these higher level skills.

**Recommendations from workplace studies:** According to an American Institute of Physics (AIP) survey of former

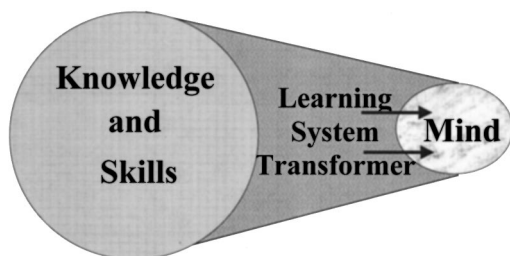


Fig. 1. A transformer model for education. The learning system is a transformer that helps student minds (the load) acquire the desired knowledge and skills (the source).

physics majors, only 15 percent of undergraduate physics graduates go on to earn a Ph.D. in physics and only half of those become professors. Eighty-two percent of B.S. physics graduates have final careers in industry, the autonomous private sector (such as small companies, software development firms, and their own consulting firms), and in government doing work in physics, engineering, mathematics, chemistry, and geosciences. Eleven percent either teach physics in high school or teach and do research in colleges.<sup>2</sup>

The predominant types of work activities of former physics majors now in industry, the private sector, and government are listed in Table II. Product design, operational planning (managing projects and groups of people), and synthesizing information (data interpretation and modeling) are very important in real world work. Figure 3 shows the frequency that former physics majors with masters degrees use various skills in their work. Bachelor and Ph.D. physicists in the workplace indicate similar skills needs. Problem solving, team work, and communication skills top the list. Physics knowledge is the least used “skill” reported in this list. AIP’s Czujko explains this, in part, by the fact that many of these former physics students now work in fields other than physics. Often, the problem solving of our former students involves subjects such as “analyzing traffic flow, climate conditions, and earthquakes.”

The skills used by former physics majors cannot be developed in a vacuum—there must be a knowledge base. But the actual content of that knowledge is probably less important than using it to help students learn to think, learn to learn, and learn the other skills requested in these studies. Trying to learn the concepts and solve the problems in one book chapter a week does not seem like a way to develop the skills needed for the workplace. According to this study, we could

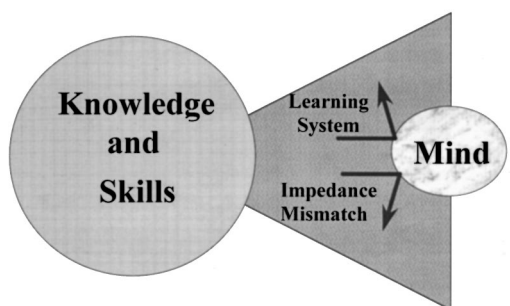


Fig. 2. A transformer with impedance mismatches that reduce students’ acquisition of the knowledge and skills.

Table I. Bloom’s taxonomy—the educational objectives developed by Bloom and a committee interested in assessing educational outcomes (Ref. 1).

Educational objective	Brief description of objective
1. Knowledge	Remembers facts, conventions, classifications, methods, and principles.
2. Comprehension	Understands and interprets phenomena when presented in verbal, pictorial, diagrammatic, graphical, or symbolic form. Can translate between these forms and uses them to extrapolate and predict.
3. Application	Applies knowledge productively to new problems without prompting concerning the principles to use. Uses productive problem solving strategies.
4. Analysis	Breaks material into its constituent parts. Detects relationships between these parts. Recognizes organizing principles and knowledge structures.
5. Synthesis	Combines previous conceptual and procedural knowledge with new to form a well integrated whole. Designs investigations and products—creative work.
6. Evaluation	Judges the value of work—its accuracy, effectiveness, and reasonableness. Are assumptions warranted? Are ideas supported by observations and consistent with each other?

meet our students’ needs better by going into greater depth with a reduced content. This would make Bloom’s committee happy.

How do the work activities and skills needed by our physics majors compare to needs expressed for engineering students in the new ABET Engineering Criteria 2000? ABET 2000 is used to evaluate college engineering programs.<sup>3</sup> The new ABET Criterion 3 requires college engineering programs to demonstrate, among other things, that their graduates have acquired the knowledge and skills listed in Table III. Interpersonal skills (teamwork), problem solving, technical writing, and communication skills are important for our physics majors and are needed by engineering students as well. Design of products and of scientific investigations is a prominent work activity for physicists (Table II) and is needed for the practice of engineering (Table III).

The 76-page *Shaping the Future* Report by the National Science Foundation (NSF) requests more inquiry (scientific investigation) in our science courses. The NSF report also

Table II. Typical work activities of former physics majors who are now in the workplace. The percent of the former students in different sectors of the workplace is also shown (Ref. 2).

Industry (42 percent)	Private sector (19 percent)
Operational planning	Consulting
Product design	Software develop
Software development	Product design
Programming	Programming
Synthesizing information	Marketing
Supervising	
Government (21 percent)	Academia (11 percent)
Operational planning	Teaching
Synthesizing information	Counseling
Product design	Providing services
Organization planning	Presenting
Modeling/Simulation	

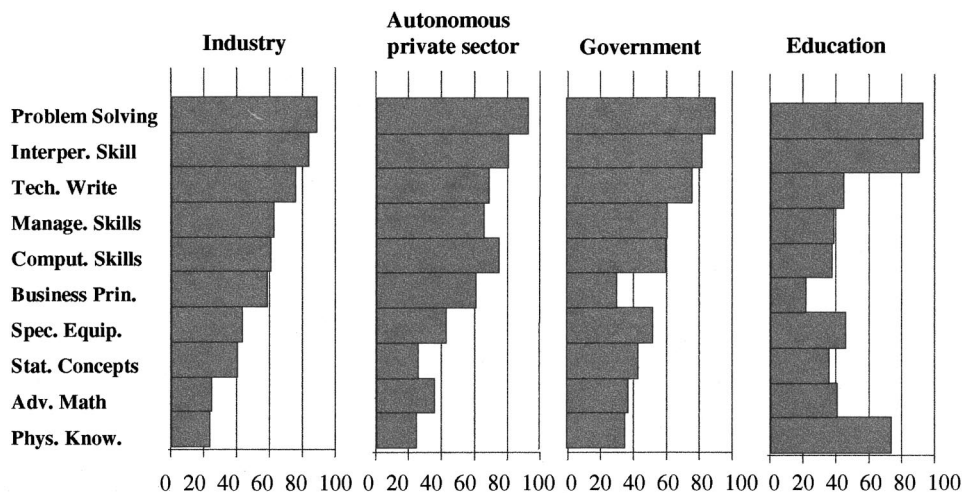


Fig. 3. Frequency with which former physics majors use different skills in the workplace. Adapted from an American Institute of Physics Workplace Skills Study (Ref. 2).

requests pedagogy that helps students develop skills such as teamwork, communication, critical thinking, and life long learning.<sup>4</sup> These three reports have considerable overlap in the desired outcomes for our education.

We can use Bloom's taxonomy and requests from the workplace studies to help choose the goals for our physics courses for science and engineering students. An example of such goals is listed in Table IV. Your goals may differ, but will hopefully reflect the extensive work represented by studies such as these. Consider very briefly the human mind that needs to acquire the knowledge and skills such as described above.

#### IV. NATURE OF THE MIND AND MATCHING IMPEDANCE

The conceptual knowledge in our courses is often in an abstract symbolic form. The symbols have precise meanings and are combined in rules that must be used correctly. In contrast, the human mind relates best to picturelike representations that emphasize qualitative features but not detailed precise information. Humans are pattern-recognition animals who try to match their new experiences with previous events.

Table III. Knowledge and skills that engineering colleges must show that their graduates have acquired in their undergraduate curriculum (ABET Criterion 3) (Ref. 3).

(a)	An ability to apply the knowledge of mathematics, science, and engineering
(b)	An ability to design and conduct experiments, as well as to analyze and interpret data
(c)	An ability to design a system, component, or process to meet desired needs
(d)	An ability to function on multi-disciplinary teams
(e)	An ability to identify, formulate, and solve engineering problems
(f)	An understanding of professional and ethical responsibility
(g)	An ability to communicate effectively
(h)	The broad education necessary to understand the impact of engineering solutions in a global and societal context
(i)	A recognition of the need for, and an ability to engage in life-long learning
(j)	A knowledge of contemporary issues
(k)	An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

The symbolic representations of physics are not common previous events. What can we do? Consider in more detail several ideas that have come from the research about learning concerning the mind's ability to acquire the concepts of physics.

**Can the average mind learn an abstract language?** A child is able to acquire at an early age the meaning of words and the rules for using them to communicate with understanding. Shortly after birth, the child's brain has  $10^{11}$  cells and about  $10^{14}$  synaptic connections between different cells. These connections are built in response to various sensory inputs to the brain. By age 4, these connections store the meaning of over 1000 words. The child with no instruction has constructed rules about using these words to communicate with others. The communication is not just repeating words and sentences that have been memorized, but is a true construction of rules. For example, the child knows that an "s" at the end of a noun means multiple objects. The child may point to her "foots." The child knows that "ed" refers to a past activity—"I goed to the store." These are not memorized statements—the child has never heard an adult use these expressions. They are the novel uses of rules that the child has developed—with no explicit instruction—just living in the world. People *can* learn an abstract symbolic system—but how is this done?

**Referents:** Linguists cannot provide a complete answer to this question. However, their studies can provide useful lessons for physics instruction. The meanings of some words are made possible by linking the words to referents—actual objects. For example, the word *ball* is learned by seeing a ball and simultaneously hearing the sound of the word or by seeing the letters *b a l l*. The word *run* has meaning by using the word as the child runs or by pointing to a running person

Table IV. One possible list of educational objectives for introductory courses for science and engineering students. The list reflects the workplace reports described in the text.

Develop the skills needed to solve <i>real</i> problems
Learn to design and conduct scientific investigations
Learn the skills needed to design a system, a component, or a process
Develop the ability to function effectively on a multidisciplinary team
Learn skills needed to engage in life long learning
Learn to communicate effectively



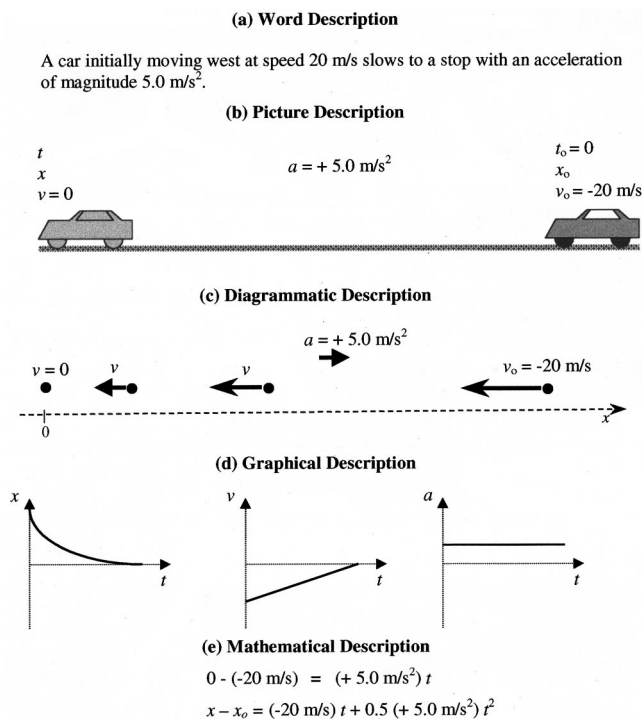


Fig. 4. A kinematics process is represented in different ways.

and saying the word. The brain stores some sort of visual image in the visual part of the cortex and an acoustic image in the audio part of the cortex. Complex connections between these different image regions help a person visualize a ball when hearing only the sound of the word or to produce the sound when seeing the ball.

What is an example of a referent for a physics quantity or concept? Consider the motion diagram in Fig. 4(c). The velocity arrows in the diagram are referents for the quantity velocity. A referent for acceleration is the velocity change arrow that we add graphically to one velocity arrow to get the next velocity arrow (we of course must divide the velocity change by the appropriate time interval). These arrows are somewhat more concrete representations for the quantities *velocity* and *acceleration* than are kinematics graphs [Fig. 4(d)] or kinematics equations [Fig. 4(e)]. Should we place more emphasis on concrete referents when *introducing* the quantities and concepts of physics? If the analogy with the child's learning of words is appropriate, then the answer is yes. It is not necessary to use these concrete referents forever—eventually the imagery in the mind gives meaning to the abstract words and symbols in physics and the referent is not necessary. But at the beginning of learning, referents certainly help. What about higher level courses and research fields in physics? Feynman diagrams provide a more concrete referent for QED interaction processes and have helped make this field accessible to a much larger number of physicists. We need referents throughout physics instruction.

**Multiple exposures to abstract concepts:** Not all words have referents—for example, the word *talent*. There is no *talent* object. Words such as this acquire meaning as a larger vocabulary is acquired. If a child exhibits a good vocabulary, a parent might praise the child and say that the child has a “talent for words.” The meaning of “talent” is acquired slowly as its use is integrated into the language over time. But even that word is linked to a concrete behavior. And, it is

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## 陆地上有轮子的交通工具

Fig. 5. A new Chinese word is defined using other Chinese words. In physics should we define new physical quantities and concepts using other quantities and concepts in abstract symbolic form?

not acquired by one or two mini-lectures. Arnold Arons has said that students need six or more exposures to a concept over an extended time interval and in a variety of contexts. We cannot expect good outcomes if a physics subject is introduced and used only during one or maybe two isolated weeks and then never seen again.

The author has had much better student learning outcomes using an instructional method that involves multiple exposures. Each large conceptual unit starts with a conceptual introduction that involves concept construction and reasoning about the world using concrete representations—referents. This is followed by an intermediate part that involves the use of the math language of physics linked to these more concrete representations that were developed earlier. Finally, students use the new concepts and previously learned concepts to solve more complex multipart problems. Students get multiple exposures to the concepts over an extended time interval and in a variety of contexts. The learning system transformer has a smooth transition between parts.

**Multiple representations:** Donald Norman has said “The powers of cognition come from abstraction and representation: the ability to represent perceptions, experiences, and thoughts in some medium other than that in which they have occurred, abstracted away from irrelevant details. This is the essence of intelligence, for if the representation and the processes are just right, then new experiences, insights, and creations can emerge.”<sup>5</sup> Simon says “Finding facilitating representations for almost any class of problem(s) should be seen as a major intellectual achievement, one that is often greatly underestimated as a significant part of both problem solving efforts in science and efforts in instructional design.”<sup>6</sup>

Suppose you are learning Chinese and a new word is defined using other words (see Fig. 5). Most of us cannot understand this new word—we do not understand the other words used in its definition. In physics instruction, we often use a similar process—a derivation that defines a new quantity or concept by using other quantities in symbolic form. If students do not understand the symbols used to define the new quantity, they will not understand the new quantity. (The definition in Fig. 5 is for the Chinese word *car*.) What can we do?

A productive strategy is to ask students early in their study of each conceptual unit to provide multiple representations for a physical process<sup>7</sup>—words, pictures or sketches, diagrams, graphs, and equations (see the example for the kinematics process in Fig. 4). A special effort is made to build links between the different representations of a quantity—for example, the different representations for acceleration as seen in the sketch, the diagram and the equation. The acceleration arrow in the motion diagram helps us understand why

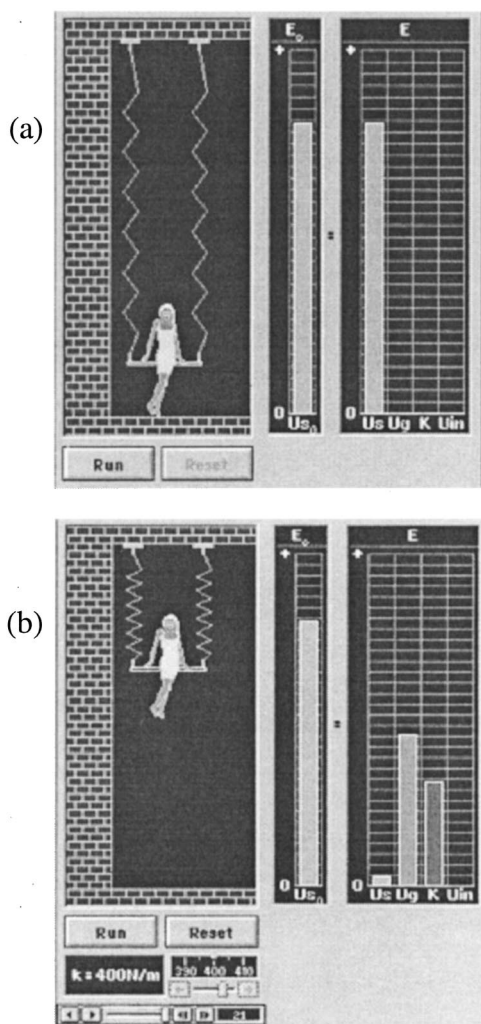


Fig. 6. A dynamic bar chart represents energy transformations during an inverse bungee jump.

the numerical value of the acceleration in the sketch and in the equations has a positive sign (even though the car's speed is decreasing).

As students gain understanding, they can be given one of the latter representations, such as an equation that represents a process. For example, describe in words and a sketch a process that is consistent with the equation below (there are many possibilities).

$$(1/2)(200 \text{ N/m})(2.0 \text{ m})^2 = (40 \text{ kg})(9.8 \text{ N/kg})y.$$

The initial elastic energy of a compressed spring (the left-hand side of the energy conservation equation) has been converted into the gravitational potential energy of a 40 kg object launched by the spring. It could be an ejector seat for a 40 kg person. Students learn to read the symbolic language of physics. We call these Jeopardy problems after the game show in which contestants are provided the answer to a question and are asked to identify the question.<sup>8</sup>

**Interactive simultaneous representations:** Reusser said: "Computers...are ideally suited to providing both representational and procedural facilitation to student's understanding."<sup>9</sup> Simulations can provide dynamic animations of processes and simultaneous physical representations of the processes. Figure 6 shows an *ActivPhysics* energy

analysis of an inverse bungee jumper.<sup>10</sup> Students see simultaneously the moving person, the changing elevation of the person, the relaxing spring, and bars representing the kinetic energy  $K$ , the gravitational potential energy  $U_g$ , and the elastic potential energy  $U_s$ . The simultaneous observation of the motion and the changing bar lengths helps to form links in student minds between the abstract energy quantities and the more concrete simulated process and the bars—called "perceptual enhancement" by Larkin and Simon.<sup>11</sup> The changing bar lengths enhance the idea of energy conservation. With the simulation, the student can move a slider to leisurely examine the whole process or parts of it. They can be asked "what if questions:" what is the effect of changing the spring's force constant. What type of energy is produced if the person's head bumps the bricks at the top of the ride?

**Start early:** During all of life, but especially in the early years, new synaptic connections are continually being made in the brain and old ones broken. The mind is continually rewiring—called plasticity. This construction of synaptic connections reinforces concepts and beliefs and makes it more difficult for the aging brain to make big changes. Linguists and cognitive scientists find that children acquire new languages more easily and with greater accuracy than adults. The ability of immigrants to learn English as a second language decreases with age of immigration (see Fig. 7). The error rate of immigrants that arrived in the US at older ages was significantly greater than the error rate for immigrants that arrived at an earlier age.<sup>12</sup> Evidently, the older immigrants' cortexes had been wired for the sounds and rules of their native language. They had difficulty integrating into their minds the new sounds and the new rules of English. Pediatric neurologist Harry Chugani said, "...who is the idiot that decided that students should learn new languages in high school?"<sup>13</sup> Should we make a similar statement about physics learning?

In summary, the beginning physics student has as a child, with no instruction, successfully acquired the meaning for words and the rules for using these words to communicate with others. The words are very abstract both in their written form and in the pressure variations caused by their sounds. Yet the child develops meaning for some of these abstract words by linking them to simultaneous visual images of real objects or real behaviors (kinesthetic experiences). The child's ability to acquire new languages decreases with age—the brain seems to become wired in a way that makes this acquisition more difficult. In physics education, students have their first physics courses well after the age when language acquisition is easier. Our traditional physics education often introduces new quantities and concepts using other quantities and concepts in abstract symbolic forms that have no meaning for the student. Imagery (referents) is seldom used when introducing new quantities and concepts. Students taught in this way are unsuccessful on conceptual tests that measure their understanding. Is this surprising?

## V. A LEARNING SYSTEM TO HELP THE MIND ACHIEVE THE DESIRED OUTCOMES

We are now faced with a considerable challenge. The world wants college graduates who have developed the complex skills such as appear in Tables II–IV and in Fig. 3. However, students' initial states when they arrive in our classes are far from this desired outcome. How do we build

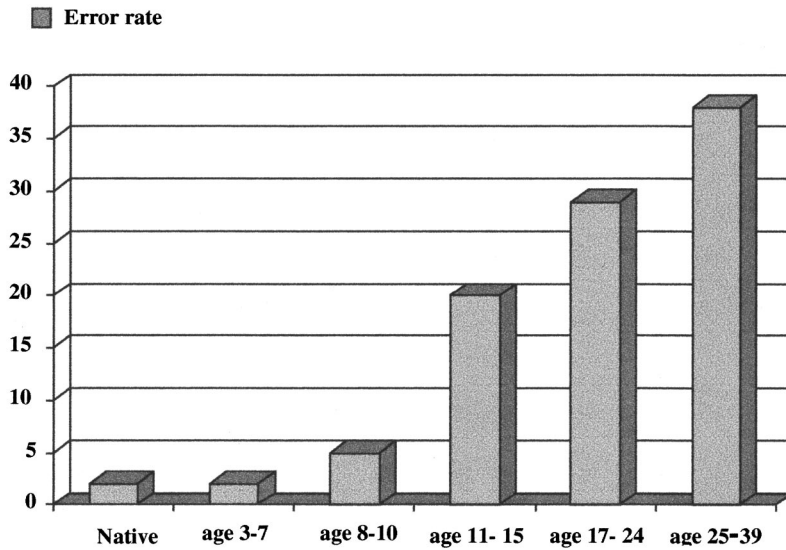


Fig. 7. The error rate in the use of English for immigrants to the United States increases as their age of immigration increases. The graph shows the results for one of twelve rules that were tested. Adapted from Johnson and Newport (Ref. 12).

learning systems that help students move from their initial states closer to the desired final state? We discussed earlier the need for referents (concrete representations), multiple representations of processes, and multiple exposures to concepts. These are important parts of the learning system transformer that help make an impedance match with the mind. How do we match the learning system to the higher level skills identified in Bloom's taxonomy and to the product design and to the design and execution of scientific investigation skills requested in the workplace studies?

**Problem Solving:** The engineering ABET 2000 standards and the AIP Workplace Skills Survey rate the ability to solve complex real world problems at or near the top of the list of skills used most frequently in the workplace. The problems of the real world differ from the problems found in most textbooks. Real world problems are poorly defined—the solver does not calculate a specified unknown quantity. Real world problems often consist of multiple smaller problems—a divide and conquer strategy is needed. This involves Bloom's analysis and should be a part of instruction and of assessment. The solver must decide what conceptual knowledge to use for each smaller problem and the unknown information that is needed to complete each problem part. This requires that the student organize and learn to access conceptual knowledge in some sort of an organized structure (see Fig. 8). Often, estimates and approximations are needed.

Additionally, there may be many possible solutions to a problem—some better than others.

Contrast this with end-of-chapter problems that ask for the exact value of one or two unknown quantities and provide all the unknown information that is needed for the problem and no more. Multi-part end-of-chapter problems and exam problems are usually broken in parts for the student (parts a, b, c and so forth). These problems have no semblance to the problems of the real world.

In recent years, alternative problem types have been developed to better help students learn the skills needed for solving real problems. Examples include: case study problems,<sup>14</sup> context rich problems,<sup>15</sup> video-enhanced problems,<sup>16</sup> Physlets,<sup>17</sup> synthesis multimedia problems,<sup>18</sup> estimation problems,<sup>19</sup> and experiment problems.<sup>20</sup> Some of these problems are now available free—see the references. They can be used with little effort in large-room meetings (lectures), in small-room meetings (recitations) and in labs.

Consider a spring launch experiment problem. Students are asked to launch a spring from a rod so that it lands in a box across the room *on the first try* (Fig. 9). They must decide the problem parts (an energy conservation problem when the stretched spring relaxes and converts its elastic energy into kinetic energy and a projectile problem after the spring leaves the rod). They must decide the unknown information that is needed to solve each part of the problem

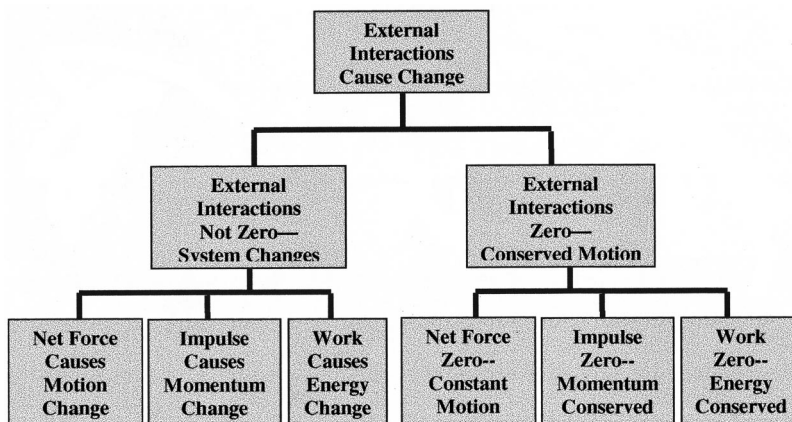


Fig. 8. A brief knowledge organization chart for mechanics.



What do we need to do to launch the spring from the end of this rod into the box across the room—on the first try.



Indicate any assumptions you made and decide if they are valid.

Fig. 9. A spring launch experiment problem.

(spring mass, spring force constant, and various dimensions of the projectile problem). They must decide the order needed to complete the solution and the unknown for each part. They complete the problem-part solutions and combine the parts to answer the big question. Finally, they decide if they have made unjustified assumptions (can they ignore air resistance or the friction of the spring sliding on the rod). The problem involves analysis, some synthesis, and evaluation.

**Design:** Design is one of the most frequent activities of physicists in the workplace (see Table II). Engineering colleges must show that their majors have developed design skills during their undergraduate careers (Table III). Design involves the synthesis of a student's knowledge to complete some task—a higher level Bloom's skill. In response to these needs, we have integrated design activities into the Ohio State University physics course for freshmen engineering honors students and into the introductory course labs for physics majors. In these labs, students design their own experiments to determine some property of a system—for example, the effective friction force between a Hot Wheels car and its level track or the energy stored in a Hot Wheels car launcher in different launching positions.<sup>21</sup>

**Epistemology:** John Dewey said that "Science education has failed because it has been so frequently presented just as so much ready-made knowledge, so much subject-matter of fact and law, rather than as the effective method of inquiry into any subject matter."<sup>22</sup> Students learn concepts by reading a book or by listening to a professor. Their beliefs come from others and are not based on their own observations and modeling of real phenomena—it is like a religious experience based on faith.<sup>23</sup>

Recently, the author has integrated into instruction an epistemological approach developed by Etkina at Rutgers University.<sup>24</sup> In her approach, students use many of the processes of science to acquire their understanding of physics. They observe phenomena, make qualitative explanations, and design experiments to test their explanations. They choose physical quantities to use in a quantitative description of these phenomena and find experimental or theoretical relationships between these quantities (laws). They use the proposed law to make predictions about the outcomes of new testing experiments. As confidence in the law grows, students apply the law in the analysis of contextually interesting problems. The students are developing the scientific investigation process skills that are needed for the workplace. Their knowledge is based on their own observations and explanations. Early testing with the author's primitive version of Etkina's promising approach indicates that students learn significantly more physics when this approach is integrated with other pedagogical features described earlier. Epistemology is an important part of two other very successful introductory

physics learning systems, Law's Workshop Physics<sup>25</sup> and Hestenes' High School Modeling Instruction.<sup>26</sup>

**Active Learning:** Consider another important pedagogical strategy—students must participate *actively* in the learning. Why is this important? William James, the early 20th century psychologist-philosopher, estimated that his personal attention span was about 10 seconds. This may be an exaggeration—or is it? According to Elesa,<sup>27</sup> during an 8-hour workday, we listen for 4 hours; we hear 2 of these 4 hours; we believe 15 minutes of what we hear; and we remember 8 minutes. In short, according to this study we remember about 3%  $[(8/240) \times 100]$  of our listening at work. If the same outcome applied to education, students would remember only 90 seconds of a 50-minute lecture. Many studies indicate that student achievement improves when students participate actively in that learning—when they interact with peers to reason about physical processes both qualitatively and quantitatively. Hake found that students in classes with lecture-based instruction had a 22% possible gain (g factor) on the conceptual Force Concept Inventory Test compared to a 43% average gain for classes using active engagement methods.<sup>28</sup> Students' talking and listening enhances their learning and hopefully improves their communications skills.

**Teamwork:** Another form of active learning involves teamwork. The ABET, NSF, and AIP studies reported in Sec. III all indicate that developing the ability to function effectively while working in teams is one of the highest priorities that the real world needs from education. According to A.P. Carnevale, "the ability of working teams to learn together is the most significant among human factors in producing income and productivity growth."<sup>29</sup>

Helping students develop the skills needed to work effectively with their peers is important for life after college. It is also important for life in school—teamwork promotes learning. In 51 high quality studies, Johnson *et al.*<sup>30</sup> found that cooperative learning classes had a 0.88 effect size greater achievement than classes with curved lecture-based instruction—almost a grade point higher achievement. In physics classes, Heller and Harbaugh<sup>31</sup> found that students who worked in cooperative groups in recitations could solve problems that instructors in traditional classes were unwilling to give their students—the problems were too difficult. The cooperative classes averaged about 20% higher than traditional classes on traditional problems given on final tests. Gautreau and Novemski<sup>32</sup> found that physics classes that emphasized group work scored about a grade point higher than traditional classes on departmental exams written by the professors teaching the traditional classes. In summary, group work offers a double benefit—it prepares students for life in the workplace while at the same time improving their learning in the classroom

**Learning to Learn:** Lauren Resnik of the University of Pittsburgh said: "School should focus its efforts on preparing people to be good adaptive learners, so they can perform effectively when situations are unpredictable and task demands change." Bereiter and Scardamalia indicate that one characteristic of experts is that they "continually invest resources in learning." It is one of the objectives of instruction in the new ABET 2000 Engineering Standards. This is all fine. But, how do we help achieve this fuzzy goal in physics courses? S. Downs described strategies that can be integrated into learning systems at all levels to help students learn bet-



Table V. Learning-to-learn strategies contrasted with traditional educational practice. Adapted from Downs (Ref. 33).

Conventional	Developing learning skills
Skills of learning are covert (hidden)	Skills of learning are made overt and discussed
The instructor explains concepts	Learners develop concepts
Learner is passive	Learner is active
Mistakes are mostly avoided	Mistakes are viewed as useful learning opportunities
Instructor poses questions and provides solutions	Instructor poses problems and discusses learner's solutions
Assessment concerns primarily the product	Concerned with the product and the process—both are important

ter how to learn.<sup>33</sup> Some of her suggestions for integrating learning-to-learn strategies into conventional instruction are summarized in Table V.

## VI. SUMMARY

Lester Thurow analyzed the history of the rises and falls of national and regional economic powers.<sup>34</sup> He wonders if a country whose education system is weak can remain an economic power in an age when *knowledge* is the foundation of the economy. What should we do? Students need the following:

- concrete, visual representations of physical quantities and concepts and to use these representations to reason about the physical world without using math;
- a linkage between the math language of physics and these concrete representations—representing physics processes in multiple ways;
- multiple exposures to the process skills and the conceptual knowledge over an extended time interval in a variety of contexts;
- to learn how to work in teams;
- more practice using epistemological science process skills; and
- active-learning pedagogy to help them become lifelong learners using skills such as listed in Table V.

<sup>1</sup>*Taxonomy of Educational Objectives: The Classification of Educational Goals, Handbook I Cognitive Domain*, edited by B. S. Bloom (David McKay Co., Inc., New York, 1956).

<sup>2</sup>Roman Czujko, "The Physics Bachelors as a passport to the workplace: Recent research results," in *The Changing Role of Physics Departments in Modern Universities*, edited by E. F. Redish and J. S. Rigden, AIP Conf. Proc. No. 399, Woodbury, NY, 1997.

<sup>3</sup>See the ABET home page at <http://www.abet.org/abethomepage.html>

<sup>4</sup>"Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology," NSF Directorate for Education and Human Resources Review of Undergraduate Education, May 15, 1996. Order through [pubs@nsf.gov](mailto:pubs@nsf.gov) or by calling (703) 306-1130. The recommendations can be seen at <http://www.ehr.nsf.gov/ehr/duedocuments/review/96139/four.htm>

<sup>5</sup>D. A. Norman, *Things That Make Us Smart* (Addison-Wesley, Reading, MA, 1993), p. 47.

<sup>6</sup>H. A. Simon, *Models of Discovery and Other Topics in the Methods of Science* (Reidel, Dordrecht, 1977).

<sup>7</sup>J. I. Heller and F. Reif, "Prescribing effective human problem solving processes: Problem description in physics," *Cognit. Instruct.* **1**, 177–216 (1984).

<sup>8</sup>A. Van Heuvelen and D. P. Maloney, "Playing physics jeopardy," *Am. J. Phys.* **67**, 252–256 (1999).

<sup>9</sup>Kurt Reusser, "Tutoring systems and pedagogical tools for understanding planning, and reflection in problem solving," in *Computers as Cognitive*

*Tools*, edited by S. P. Lajoie and S. J. Derry (Lawrence Erlbaum Assoc., Hillsdale, NJ, 1993), p. 147.

<sup>10</sup>Alan Van Heuvelen, *ActivPhysics 1* (Addison-Wesley-Longman, Palo Alto, CA, 1998); Alan Van Heuvelen and P. D'Alessandris, *ActivPhysics 2* (Addison-Wesley, Longman, Palo Alto, CA, 2000).

<sup>11</sup>J. H. Larkin and H. Simon, "Why a diagram is (sometimes) worth ten thousand words," *Cogn. Sci.* **11**, 65–99 (1987).

<sup>12</sup>Adapted from Fig. 13.3, p. 271 of J. S. Johnson and E. L. Newport, "Critical period effects in second language learning: the influence of maturational state on the acquisition of English as a second language," in *Brain Development and Cognition: A Reader*, edited by M. H. Johnson (Blackwell, Cambridge, MA, 1993).

<sup>13</sup>R. Kotula, *Inside the Brain: Revolutionary Discoveries of How the Mind Works* (Andrews McMeel, Kansas City, 1997), p. 36.

<sup>14</sup>Alan Van Heuvelen, "Overview case-study physics," *Am. J. Phys.* **59**, 898–907 (1991).

<sup>15</sup>P. Heller, R. Keith, and S. Anderson, "Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving," *Am. J. Phys.* **60**, 627–636 (1992); and P. Heller and M. Hollabagh, "Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups," *ibid.* **60**, 637–644 (1992). See <http://www.physics.umn.edu/groups/phised/Research/CRP/onlineArchive/ola.html>

<sup>16</sup>A. P. Titus, Ph.D. dissertation, North Carolina State University, 1998.

<sup>17</sup>See the Wolfgang Christian's Physlets web site at <http://webphysics.davidson.edu/Applets/Applets.html>

<sup>18</sup>Alan Van Heuvelen, "Using interactive simulations to enhance conceptual development and problem solving skills," *Proceedings of the International Conference on Physics Education*, College Park, MD, edited by E. F. Redish and J. Rigden (American Institute of Physics, New York, 1997), pp. 1119–1136. The activities are part of a comprehensive multimedia product: A. Van Heuvelen, *ActivPhysics 1 (Version 1.1)* (Addison Wesley Longman, San Francisco, 2000); and A. Van Heuvelen and P. D. D'Alessandris, *ActivPhysics 2* (Addison Wesley Longman, San Francisco, 1999).

<sup>19</sup>Glenn M. Julian, "A demonstration on every exam," *Phys. Teach.* **33**, 248–250 (1995).

<sup>20</sup>Alan Van Heuvelen, "Experiment problems for mechanics," *Phys. Teach.* **33**, 176–182 (1995); A. Van Heuvelen, L. Allen, and P. Mihás, "Experiment problems for electricity and magnetism," *ibid.* **37**, 482–485 (1999). See [http://www.physics.ohio-state.edu/phisedu/people/vanheu/projects/expm\\_pbm.htm](http://www.physics.ohio-state.edu/phisedu/people/vanheu/projects/expm_pbm.htm)

<sup>21</sup>David Van Domelen, Ph.D. dissertation, Ohio State University, 2000.

<sup>22</sup>*John Dewey on Education: Selected Writings*, edited by R. D. Archambault (Random House, New York, 1964), p. 182.

<sup>23</sup>M. Singham, "Teaching and propaganda," *Phys. Today* **54**, 54–55 (2000).

<sup>24</sup>E. Etkina (unpublished).

<sup>25</sup>P. W. Laws, "Calculus-based physics without lectures," *Phys. Today* **44**, 24–31 (1991).

<sup>26</sup>D. Hestenes, "Toward a modeling theory of physics instruction," *Am. J. Phys.* **55**, 440–454 (1987).

<sup>27</sup>J. G. Elsea, *First Impression, Best Impression* (Fireside Books, New York, 1986).

<sup>28</sup>R. R. Hake, "Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses," *Am. J. Phys.* **66**, 64–74 (1998).

<sup>29</sup>A. P. Carnevale, *Human Capital: A High Yield Corporate Investment* (American Society for Training and Development, Alexandria, VA, 1983).

<sup>30</sup>D. W. Johnson, R. T. Johnson, and K. A. Smith, *Active Learning: Cooperation in the College Classroom* (Interaction Book Company, Edina, MN, 1998).

<sup>31</sup>P. Heller, R. Keith, and S. Anderson, "Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving," *Am. J. Phys.* **60**, 627–636 (1992).

<sup>32</sup>R. Gautreau and L. Novesky, "Concepts first—A small group approach to physics learning," *Am. J. Phys.* **65**, 418–428 (1997).

<sup>33</sup>S. S. Downs, "Developing learning skills," in *Learning Management: Emerging Directions for Learning to Learn in the Workplace*, edited by M. E. Cheren (Ohio State University, Columbus, OH, 1987), p. 37. See also J. D. Novak and D. B. Gowin, *Learning How to Learn* (Cambridge University Press, New York, 1984).

<sup>34</sup>L. C. Thurow, *Building Wealth—The New Rules for Individuals, Companies, and Nations in a Knowledge-Based Economy* (Harper Collins, New York, 1999).