New Directions of Research on Undergraduate Physics Education

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Welcome to the international conference, “Physics for All,” that has brought together many teachers of physics from all over the world. As physics educators, many of us have had the experience that our students do not seem to be learning physics very well, not all of them, anyway. It used to be that it was all right to only worry about the few percent that were able to learn well when we taught physics in our traditional way. But now, in these increasingly technical times, it is essential for us to pay more attention to more of our students. This is what we mean by “Physics for All.”

As a result of this shift in view, a few decades ago, a number of physicists began to treat the teaching of physics as a scientific problem, and to use their skills as scientists to solve the question of how we can teach more students more effectively. This is not a trivial problem. It is harder than nuclear physics and it is harder than rocket science. Physics education researchers around the world now treat these issues as scientific research problems and ask a series of important questions: What is actually going on in our classes? How can we better accomplish our goals? How can we better understand what our real goals are for our students?

As scientists, we understand that we must first observe a phenomenon carefully. It is not enough to look at the final examinations and to say this percentage of students has passed and this percentage of students has failed. We need to better understand the process by which our students learn. So physics education research has developed a series of observational tools including: detailed interviews with individual students, having them write out explanations of what they are thinking, testing before and after instruction, and videotaping student work in group environments. I will talk about some of these in this presentation. I have organized part of this talk into lessons – brief principles summarizing what we have learned, often from years of extensive research.

Lesson 1: Concepts don’t come for free!

The first lesson we have learned in physics education research is that the concepts don’t come for free. In traditional teaching, we often don’t really teach the basic meaning of physics, the concepts, the underlying ideas, but we expect them to come along automatically when students learn equations and solve problems. For some students this works, but they are very few. And there has been extensive research that has demonstrated that in most areas of physics introductory students have common misunderstandings, even after they have heard instruction on the topic. There are surveys that have been developed to probe student understanding of concepts; a number of them are available in the CD-ROM in my book [1], and more are listed on my website. [2]

Getting students to solve algorithmic problems is not enough

One of the surprising things that was learned quite early was that when students learn to solve problem by algorithmic rules, they do not necessarily also get conceptual learning. Eric Mazur from

Harvard University demonstrated this with his students. [3] Harvard is among the top universities in America the students are of very high quality. He gave the problem shown in Fig. 1 to his students on a test. This is difficult problem. You have to solve a set of coupled equations to find the answer.

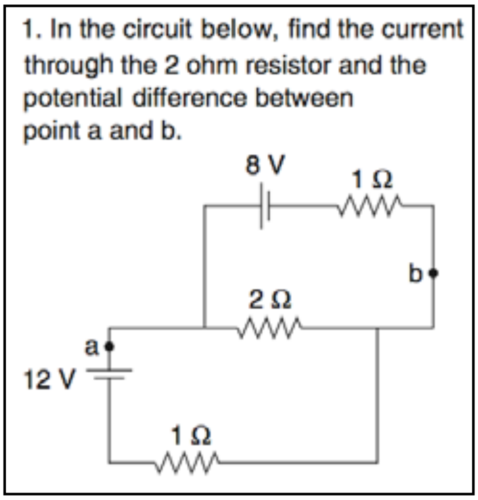


Fig. 1

On the same test he also gave the problem shown in Fig. 2. In that circuit, students were asked to explain what happens when the switch is closed. When the switch is open it is simply a single loop of current with three identical bulbs. They will all be lit identically. And now when you close the switch, what happens? It's not such a difficult problem. The third bulb is cut out entirely and other two become brighter.

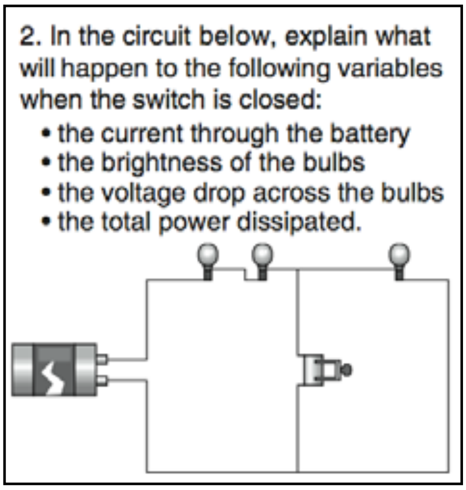


Fig. 2

But Mazur found that about 75% of his students were able to do the first problem, but the fewer than half of them could do the second. They felt that the second problem was much more difficult. The conclusion he drew, and that has since been demonstrated widely, was that students can frequently solve complex problems using memorized rules, without having a good understanding of the underlying physics concepts.

Lesson 2: The problem is widespread!

The conceptual surveys that I mentioned that were developed beginning about 1985 had very simple questions. But because they were based on interviews done with many students, the people who wrote these surveys knew what the students' common misunderstandings were. Those common misunderstandings were chosen as the distracting answers. As a result, many students found them very attractive. These surveys could be easily given to many students and by now, tens of thousands of students have taken them.

An Example: The Force Concept Inventory (FCI)

In 1992, David Hestenes with his colleagues, published a survey called The Force Concept Inventory. This is a 30 item multiple choice test to probe basic ideas in mechanics. It was written in common speech rather than using technical terms, and it used commonly held wrong answers as attractive distracters.

Fig. 3 is one of the Newton's third law questions. Notice the answer in item (C), which says neither exerts a force on the other, the car simply gets smashed because it gets in the way of the truck. Now no sensible physicists would ever consider giving this as a possible answer. And most university students will not say this if they have had a physics course. But high school students often choose this answer. Notice that there is nothing in the question about action and reaction. So the technical terms that are often used to cue Newton's third law are absent (intentionally).

A large truck collides head-on with a small compact car. During the collision:
(A) the truck exerts a greater amount of force on the car than the car exerts on the truck.
(B) the car exerts a greater amount of force on the truck than the truck exerts on the car.
(C) neither exerts a force on the other, the car gets smashed simply because it gets in the way of the truck.
(D) the truck exerts a force on the car but the car does not exert a force on the truck.
(E) the truck exerts the same amount of force on the car as the car exerts on the truck.

Fig. 3

I gave the FCI in my own university class of 178 engineers in a year that I taught using traditional lecture and recitations. Before instruction, 70% of the students chose that the truck would exert more force because it was bigger (A), and only 26% chose the correct answer (E). These students had all successfully completed high school physics, in which this was supposedly taught. After instruction we made great improvement. Now 51% of the students got the correct answer, but almost half were still giving the same wrong answer. This is not very satisfactory. After reformed instruction that I will tell you about in a moment, 83% of the students chose the correct answer.

These results are common. Studies with thousands of students show that they do poorly on the FCI before they have physics, and that as a result of physics instruction they gain very little.

Lesson 3: Many students have conceptual difficulties throughout introductory physics!

Our third lesson is that these problems are not restricted to mechanics; many students have conceptual difficulties in many different areas of physics all through the curricula. The research demonstrating this was done in the '90s by many researchers in many different countries, including many of the people in this audience. [4]

Curricular options: Research-based materials

Once the commonest difficulties had been determined, various curricula began to be developed based on this research knowledge. The research that helps us understand what difficulties the students have can also help us to create curricula that help students learn more effectively. In the '90s a wide variety of reformed materials were developed that take into account the common confusions and that help students build a better understanding of the subject through well-designed activities.

Lesson 4: It's what students <u>do</u> that counts!

Our fourth lesson is that it is not what we say to the students that matters. It's what the students actually do. If we give a lecture to a student, and the student sits and thinks and says, "Oh, do I understand this?" writes it down, says, "I do not understand this! What are other ways of looking at it?" If the student does all this work while I lecture, my lecture can be very effective. But not very many students do this. They tend to just write down what we say and then try to memorize it without doing the work to make sense of it. What research-based curricula try to do is to teach students how to do the kind of thinking that is necessary to build a good knowledge of physics.

This is the difference between physics for physicists and physics for all. To reach more students, we must not only present the physics in a physicist's way for only those students who are physicists. Students who want to be physicists are dedicated, they are convinced of importance of physics, and as a result, they do what they need to do for themselves. The rest of our students need to be helped to learn how to learn physics effectively. As teachers it is our job to figure out how to help them do this. Our students have to learn that it is important to make sense of physics. They have to look for coherence, not be satisfied with memorizing bits and pieces. Another important thing is for them to reflect on their knowledge and to try to reconcile their personal knowledge with the knowledge they are learning. There are many curricula that have been developed that encourage these skills. I'm not going to talk about these in detail here, but I will talk about some of them in the workshop I give tomorrow with a couple of my colleagues. Here I just mention briefly two curricular models.

Workshop physics

One reformed curriculum the workshop physics model [5], developed by Priscilla Laws and her colleagues of Dickinson College. She will be reporting on this curriculum later in this meeting.

Workshop physics replaces the lecture entirely by laboratories where the students use high technology computers and data acquisition devices to quickly and easily obtain data and explore the physical world in quantitative detail. It is not a free exploration. It is highly guided. There is an instructor to keep the task moving along and to create group discussions so that different views can be brought together. This is typically done in a small class with 20-30 students.

Tutorials

If you have a large class like I do, with 200 students, one way to get more interaction is to break your class up for one hour a week and have them meet in groups of 20-30. In this situation I have them do tutorials in which they work on research-based worksheets.[6] The instructor, a professor or a teaching assistant, serves as a facilitator who wanders around and ask questions but does not lecture or explain. The worksheets walk students through reasoning qualitatively and conceptually.

Different instructional models produce better conceptual gains

To compare these and other reform curricula, my colleagues and I at Maryland did a quantitative study using the FCI. [7] We gave the FCI before and after instruction in the first semester of university physics in 15 universities including 3 large research based universities including my own. In the United States this class is mostly taken by engineers, is calculus based, and the students have taken a high school course in physics. Our control group were traditional classes – three lectures per week plus one hour a week of small group session in which teaching assistants solved problems and helped answer students' questions.

In one reformed model, the lecture remained traditional, but the small group session was replaced by a research-based worksheet guided tutorial. [6] In a second reformed model, the small group session was replaced by a research-based group-problem solving session. [8] A fourth model was workshop physics. [5] We observed both at the places where these methods were developed, and at other universities who had adapted these reforms to their own situations.

It is difficult to directly compare results from different universities where students may come in with different average scores. Students from Harvard score 70% of the FCI correct before they take the course, my engineers score 50% correct before the course, and at some other schools they only score 30% before the course. It's not fair to compare the final scores. Instead, we compares a kind of efficiency: the *fraction of the possible gain*, the class's posttest average minus the pretest average divide by 100 minus pretest average (h = (post – pre)/(100 – pre)).

What we found is that the traditional course got a fractional gain of less than 20% (though with a wide spread). Modifying one hour of instruction using research-based methods improved the result to nearly 35% (and narrowed the spread significantly, suggesting that the impact of the particular instructor on the learning needed for this test was reduced). First-year implementations of workshop physics averaged 40% and were better than the other methods tested. A mature implementation of workshop physics at Dickinson College scored 75%. Fig. 4 shows the distribution of the histograms for the different classes.

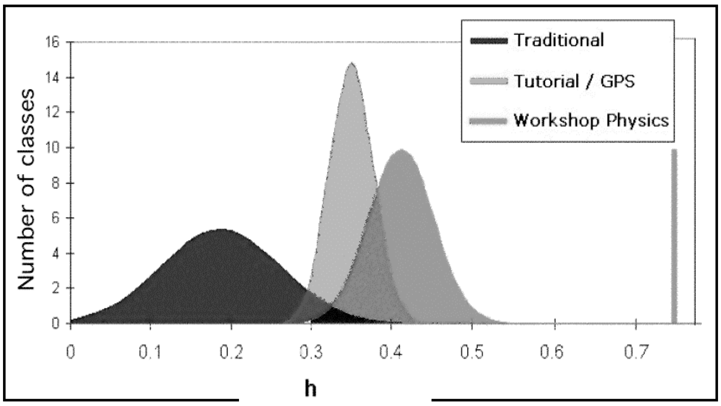


Fig. 4

Lesson 5: We can do better!

These results and many others show that we can make substantial gains. By paying attention to what students know and how they learn, we can create environments that produce more effective concept learning than traditional methods. These reforms don't necessary take a lot of time. One hour a week made a big difference, almost doubling the gains compared to traditional instruction.

Concepts are important.

We certainly want our physics students to be able to solve problems, but the algorithmic problem solving that is often the focus of the university physics class is not really the point. When we substitute tutorials for an hour a week of working on problems, our students don't do worse on algorithmic problems, despite not having many hours watching teaching assistants solve them. You might ask why should I bother about these concepts, if the students can do algorithmic problem solving without them. The reason is that the concepts are what underlies physics. It's what tells you what the physics is <u>about</u>. Otherwise physics just becomes memorization and symbol manipulation.

But concepts are not enough.

But these concepts are not sufficient. They are only a part of the story. We want our students to learn to think like scientists. They need to care about coherence. They need to have physical intuition. They need to build confidence. They need to learn to think with mathematics to solve complex problems. We have these deeper goals, even for the students who are not going to be physicists.

We need a theory of thinking and learning to see where to go next.

In doing science, we don't simply observe the world and make a list of what happens. We try to make sense of it. We need to develop some kind of theoretical structure, some way of thinking about it that lets us understand the mechanism underlying the phenomenon. So here we need some better understanding about how students think and learn to understand where to go next. Once we begin to learn how the student mind works, it helps us make sense of some things we see students say and do that at first seem strange. It also helps us to find clear goals for our instruction, to create more effective environments, and to develop better tools of observation and evaluation.

Science is an interaction between the real world and the minds of scientists

An important realization is that science is not just about how the world works. Science is an interaction between the world and the minds of the scientists. If we only think we are studying one end of the interaction, then we are mistaking a critical part.

A Traditional Theory of Student Learning

The traditional model of student learning is very simple. You open the student's head. You put knowledge in and the student either has it or does not. Physics teachers don't really think this is the way students learn. But often we function as if we did. Many teachers assume all we need to do is tell our students the physics. Many teachers are satisfied if their students can give an answer in one case in any form at all because then "they know it". But we need a more sophisticated model. I'm not going to show you details of this, but I will make two points that have been learned and I will give two examples of how this more complex model changes our perceptions of students.

There are three components to the understanding of human thinking. First is the fundamental mechanism in the brain, neuroscience. As a physicist I want to have an "atomic model" of my theory. It's like developing physics theory at the time of Maxwell. For Maxwell, the fact of knowing that matter was made up of atoms, even if you did not know the size, even if you did not know the forces, was enough to build transport theory, was enough to understand how chemical reactions were taking place. You didn't need to know a lot of detail. That's where I feel we are with neuroscience. We cannot build understanding from the neuroscience – yet. But understanding how a neuron works helps. Cognitive science is the second component. There, they study the fundamental mechanisms of thinking. They do what for us would be zero-friction experiments, eliminating all confusing factors to focus on fundamental mechanism. But that focusing removes some critical issues for real world situations. So you have to look at the third component, behavioral science, to deal with real people, doing real things in real situations. And much is known here as well. I'll describe two ideas from what we have been learning: activation/association and compilation/binding.

Activation / Association

The fundamental idea that is learned in neuroscience is that when you think about something particular groups of neurons are activated electrically. They send electrical pulses called action potentials to other neurons. A second principle that is learned both from neuroscience and from cognitive science is that the brain works fundamentally through association. Neurons corresponding to one sensation or thought or idea connect to others and can activate them. Our memory contains huge amounts of information. We remember things from 50 years ago. We remember yesterday. But we don't necessarily have easy access to all these resources. The system is not well organized. It's not date stamped and it is not indexed. You can't Google your brain! In order to get information you sometimes have to associate through a long chain of memories.

Which bits of a long-term memory are activated may depend not only on sensory input (such as what our students hear us say), but on other things that are activated in the brain at the time. One way of understanding student thinking is that the brain has certain basic tools, "atomic" resources – simple primitive reasoning ideas such as "more cause produces more effect". When we perceive a real situation, we map that basic resource into a more complex, concrete idea, such as "more force is needed to produce more velocity".

Activating the wrong resources

Let me give one example of how some student difficulties can be understood by realizing that they are activating natural, but inappropriate, resources. I have a story that happened to me that goes with the slides but we did not have time to translate it so I thought one way to translate it that would help you to make sense of it would be to do a kind of a drama. I would like to do it as Bunraku with two puppets. I would put on a black and become a narrator and have the puppets speak. But I have no black costume, no puppets, so you will have to use your imagination and I will use these props (a hat and a scarf) to symbolize the puppets.

Two resources

Our first character is an old bearded professor, who is in his office. Now over here we have a hard working young student with a problem. She speaks. "Professor, I have attended your wise lectures on mechanical energy and I have understood them completely. I feel very confident about my understanding of energy. But I always get the problems wrong. You must help me." The Professor responds, "I am certain that I can help you. But first I must understand what your difficulties are. So let us imagine that I take an object and I drop it. " And I dropped an object. "So what happens about the energy?" The student responds confidently, "It is <u>not</u> conserved." Professor: "What about the potential energy?" The student responds, "Oh, professor, I have no problem with this at all. I know the potential energy. It is mgh, h is the height. As it descends, the height changes. So it changes. As I said, the energy changes." The sage responds, "Ah, now what about the kinetic energy?" The student continues with confidence, "But I know this, too! This is $\frac{1}{2}mv^2$. As the object falls, it gets faster. So the kinetic energy <u>also</u> changes, and therefore the energy is not conserved." At that point, I understood what was going on. The student was using what we call *feature analysis*, rather than *compensation*. Feature analysis is the appropriate thing if you are watching animé and you see a character. A few minutes later, a different character comes in. You think it's a different character. Is it different? Is it the same character in disguise? So you look carefully. Well, the eyes are different. Then you look again and find the noses are also different. So you conclude they must be different characters. The underlying reasoning principle you are using here is "different plus different equals more different". This is what the student was using. What we want the student to use is compensation – one quantity increases as another decreases. So what the Professor did was say, "Aha, young student. Now please sit and imagine that you have in your hand twenty 1,000 yen notes." And the student sits and imagines holding in notes her hand. Then the Professor says, "Now begin passing those notes to me, one at a time." She does. And he says, "Is the number of the notes you have conserved?" "No." "Is the number of the notes I have conserved?" "No." "Now, is the total number of the notes in the..." and she went "Ah!" and from then on, there was no problem.

It was not that she did not have the tools, that she did not have the reasoning. To understand the issue of energy conservation, she had not used the proper resources, though she was thinking of them as numbers and calculating. She wasn't thinking of relating the numbers in appropriate way.

And the true hero in this story is not Professor Redish. The true hero is the young graduate student, Jonathan Tuminaro, who for two years had been observing videotapes of students' reasoning and had identified in many students this resource of feature analysis [9] and told the professor, who then was able to see it and use it appropriately.

Compilation / Binding

A second example is what I call compilation or the binding problem. As we learn, we bring together many different pieces of knowledge, binding them into something that we can use as the single unit. When you look at a cup of tea, this very fact that you see a cup of tea is amazing. You are getting information through your eyes, which comes into the visual cortex in the back of your brain. You are getting information from your touch, which comes in at the top of your brain. From your smell and taste you are getting information that comes in to the front of your brain. From your long-term memory you activate what the tea will taste like, what it will feel like, what this particular kind of tea will do to you, whether wake you up or calm you down. These come from all over the brain, very far apart as neurons go, but the whole is unified into the sense of a single thing. That you sense one single object, the tea, happens in a very complex way that is still poorly understood in neuroscience.

This sort of thing happens when you are an infant and you learn to create objects. But as we learn other things, as we learn to read a graph, to take derivatives, these things become bound in a complex way and it's very hard to take your own knowledge apart for yourself. I will give you an example of how understanding this binding can change the way we look at student learning.

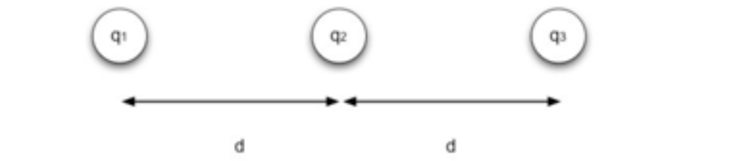
Reverse engineering

We can't usually "unpack" what we know. But we can reverse-engineer them and figure out what is in the knowledge, and sometimes watching students work helps us understand this.

We watched three students solve a simple problem.

In my second example we watched three students solve a simple problem. These are in a class, not of engineers, but of bio-science majors. They take college physics: algebra only, no calculus. The students are actually sophisticated scientists. They have studied organic chemistry, genetics, and cell biology. They are not naïve, but they know very little physics and are not used to using much math.

Consider the problem shown in Fig. 5. Think about the problem for a moment. Many of you know the answer right away. Some of you might take a minute, maybe two, to work it out. Typically what I observe is that a physics teacher who has recently taught a course on electricity can typically tell me the answer in no time at all, immediately say “It’s got to be opposite sign to give a force in the opposite direction. The force goes like the square of distance. It’s twice as far away. The answer is -4*Q*.”



In the figure above three charged particles lie on a straight line and are separated by distances *d*. Charges q_1 and q_2 are held fixed. Charge q_3 is free to move but happens to be in equilibrium (no net electrostatic force acts on it). If charge q_2 has the value Q, what value must the charge q_1 have?

Fig. 5

We videotaped three students working on this problem. They worked on it for 45 minutes. Compared to 3 seconds, 2700 seconds (= 60 x 45) is three orders of magnitude larger. Is this a waste of their time? What were they doing? But we watched them carefully and we believe that it was an extremely effective use of their time. Because the simple statement that it’s -4*Q*, requires much knowledge from Newtonian mechanics. And Newtonian mechanics was new to the students and had not yet been compiled into simple knowledge so that it was immediately obvious to them.

It was time well spent!

They had only learned Newtonian mechanics a few months earlier. In their work on the problem they spent more than half the time working on the issues of force. The problem is complicated. There are six forces acting. Which should they pay attention to? They got the answer they needed about which forces to pay attention to and then they lost it. They did this three times. Then the teaching assistant who was observing said, “Why don’t you draw a picture?” They drew a picture that nailed it down for them. So one of the things they learned was drawing a picture helps you nail it down. In all, we saw that they were in the process of binding and compiling their knowledge of Newton’s laws. When we went through this problem in detail, we decided there were at least twenty different items of physics they needed to know to solve the problem.[10]

Summary

I have been teaching physics for over 35 years and doing physics education research for almost 15, and I have learned a few things. First, it’s very important to think about what it is you really want to accomplish in your teaching. We tend to focus on superficial issues to say, “I want to cover these chapters,” and not to think about what learning we want our students to have in the end.

Second, it’s essential to understand where your students are and what they can do. If you have a mismatch between what your students are able to learn and what you give them, they will learn it in a superficial way that they will be unable to consolidate or build upon.

Third, it’s what the <u>students</u> do that matters most for their learning, not what the instructors do. Therefore, it is crucial for us to consider the environments in which they will work in order to learn what we are giving them. If we can help them create effective learning environments, for most students, that can be much more effective than simply leaving it to them.

And finally what we are asking our students to do in learning physics is much harder than we sometimes think. Because we have already learned it ourselves, we sometimes forget the pain. I think it's like childbirth. Once you have a child, you tend to forget the pain (so that you will have another one). Learning physics is a bit like that.

Lesson 6: You don't have to do it all by yourself!

This is the most important lesson of all. Learning to understand our students' learning is hard work, but you don't have to do it by yourself. We are a community of researchers and educators and scholars from all over the world. From improving of our knowledge of students, both observationally and from fundamental theory, we can better understand, both what we can do and what we need to do. We can share our materials and adapt them to our local environments.

Finally, for more information, I have a small book on this subject. [1] The entire book is available on the web [2], and this website of the University of Maryland's Physics Education Research Group also has links to physics education resources and groups all over the world, as well as references, lessons, and research tools.

Thank you very much. Have a wonderful conference.

I would like to gratefully acknowledge the contribution of Mariko Lang. Her excellent transcription of my spoken talk greatly facilitated the construction of this text version.

[1] Edward F. Redish: *Teaching Physics with the Physics Suite*, John Wiley and Sons, Inc. 2003, *http://www2.physics.umd.edu/~redish/Book/.*

[2] The website of the University of Maryland's Physics Education Research Group, *http://www.physics.umd.edu/perg/.*

[3] Eric Mazur, *Peer Instruction: A User's Manual*, Prentice Hall, 1997.

[4] L. C. McDermott and E. F. Redish, American Journal of Physics, Vol. 67, 755-767 (1999); *http://www.physics.umd.edu/rgroups/ripe/papers/rlpre.pdf*

[5] Priscilla Laws, *Workshop Physics Activity Guide*, John Wiley & Sons, 1997

[6] L. C. McDermott, et al., *Tutorials In Introductory Physics*, Prentice Hall, NY, 1998

[7] E. F. Redish, J. M. Saul, and R. S. Steinberg, American Journal of Physics, Vol. 65, 45-54 (1998) *http://www.physics.umd.edu/perg/papers/redish/mblpre.PDF*

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[9] J. Tuminaro, *A cognitive framework for analyzing and describing introductory students' use and understanding of mathematics in physics*, PhD dissertation, University of Maryland (2004), *http://www.physics.umd.edu/perg/dissertations/Tuminaro/*.

[10] E. Redish, R. Scherr, and J. Tuminaro, *The Physics Teacher*, Vol. 44, 293-400 (May 2006)