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ABSTRACT

This paper examines the nature of physics students' knowledge, the means to identify alternative conceptions, and possible methods to overcome misconceptions. This examination is a survey of the techniques and ideas of a large number of researchers who are seeking their own solutions to this problem. An examination of the nature of knowledge within the classroom and the shortfalls of educational models that provide some background for a discussion of effective teaching methodology are included. This report continues by examining the source of students' alternative conceptions both within and outside of the classroom, and the methods for identifying these alternative conceptions. Three potential techniques for overcoming alternative conceptions and establishing a richer understanding of physics knowledge within the classroom are outlined. (Contains 24 references and 4 appendices.) (DDR)

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An Overview of Techniques for Identifying, Acknowledging and Overcoming Alternate Conceptions in Physics Education

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I. Introduction

Mark Twain once observed, “It’s not what you don’t know that hurts you. It’s what you know that ain’t so.” What Twain so blithely stated so many years ago, modern cognitive psychologists are in the process of rediscovering today. Every individual approaches learning with a set of assumptions of how the world operates. Sometimes these are conscious observations and at other times they are unconscious biases that can filter what we perceive and learn. Johnson-Lairde in the work *Mental Models* reiterates Twain’s comment in a less pithy manner: "Our view of the world is causally dependent both on the way the world is and on the way we are. There is an obvious but important corollary: all our knowledge of the world depends on our ability to construct models of it."[1]

These mental models reflect all that we have experienced and the many assumptions that we make about the world around us. It is important to note at this point that not all *preconceptions* are *misconceptions*. In this paper, the term *alternative conception* is used for all preconceptions or models that have the potential to interfere with future learning. This paper examines the nature of physics students’ knowledge, the means to identify alternate conceptions, and the possible methods to overcome misconceptions. This examination is not meant to be a comprehensive solution to the difficult problem of alternate conceptions, but a survey of the techniques and ideas of a large number of researchers who are seeking their own solutions to this persistent problem in physics education today.

The paper begins by examining the nature of knowledge within the classroom and the shortfalls of standard educational models. This provides some background for the discussion of effective teaching methodology later in the paper. The paper continues by examining the source of students' alternative conceptions, both within and outside of the classroom, and the methods for identifying these alternative conceptions. The paper concludes with three potential techniques for overcoming alternative conceptions and establishing a richer understanding of physics knowledge within the classroom.

II. The Nature of Knowledge in Physics

There is mounting evidence that science students possess alternate conceptions that tenaciously resist change. Analysis of errors on qualitative tests along with interview data suggest that students are not simply failing to learn new material, but are maintaining alternative frameworks.[2] These alternate conceptions are preventing the integration and acceptance of new concepts. In the book *Project 2061: Science for All Americans*, the writers comment:

> "Cognitive research is revealing that even with what is taken to be good instruction, many students, including academically talented ones, understand less than we think they do. With determination, students taking an examination are commonly able to identify what they have been told or what they have read; careful probing, however, often shows that their understanding is limited or distorted, if not altogether wrong."[3]

These alternate conceptions can even exist in advanced physics students, who though proficient in the use of formulae, have no understanding of the scientific principles involved.[4] The conceptual frameworks that students possess upon entering a physics

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[1] Johnson-Lairde, P.N., "Mental Models", Cambridge: Cambridge University Press, 1983

[2] Driver & Easley, 1978; McDermott, 1984

[3] American Association for the Advancement of Science, "Science for All Americans: Project 2061" New York: Oxford University Press, (1990), p. 198

[4] Clement, 1983; Halloun & Hestenes, 1985

course has a profound impact on the material that they learn. Hestenes and Halloun suggest that "...physics instruction in high school should have a different emphasis than it has in college. The initial knowledge state is even more critical to the success of high school instruction. The low scores indicate that students are prone to misinterpreting almost everything that they see and hear in the physics class."[5] "Unaware that their own ideas about [a concept] differ drastically from those of the teacher," they continue, "those students systematically misunderstand what they hear and read in introductory physics."[6] These students cannot understand why they fail when solving problems and resort to memorizing meaningless formulae and rote procedures, thus becoming disillusioned with the course. The change must occur in the initial physics course the student experiences, typically in high school. If the student leaves this first course without internalizing the information presented, they risk future frustration.

David Perkins in his book *Smart Schools* offers some insight into this problem by what he describes as *fragile knowledge*[7] in students. Students, who although well educated, still do not know what they ought to know or are unable to utilize the knowledge they retain. This is especially true for the subjects of mathematics and science where students can become proficient through the memorization of rote formulae and laws without a deep understanding of their meaning. They are able to pass almost any examination through the memorization of basic problem solving skills. They learn the process to solve one type of word problem and use the same technique to solve similar problems without any deep understanding of the principles involved. These are

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[5] I. A. Halloun and D. Hestenes, "The initial knowledge state of college physics students", Am. J. Phys. **53**, 1045 (1985).

[6] Hestenes, D. (1996). "Modeling Methodology For Physics Teachers" 1996 Proceedings of the International Conference on Undergraduate Physics, College Park, p. 4.

the same students who years later can still espouse the law or formula, but when questioned deeply on the conceptual basis of the law or principle, falter. As an illustration of this point, in the film, *A Private Universe*[8], Harvard University graduates are given a battery, a light bulb, and a piece of wire and are asked to make the light bulb light. All of these students had been exposed to the concept of electrical circuits at least at one point in their education, but only a few of the graduates were able to apply this knowledge usefully. They had either forgotten the topic or compartmentalized the knowledge without making connections to real life situations. Perkins refers to this latter type of knowledge, which lies latent in the mind, *as inert knowledge*[9].

Inert knowledge. Inert knowledge is the knowledge that will come to mind when the student is tested, but otherwise remains inaccessible, and therefore, quite useless to the student in everyday life. It is knowledge that has been memorized, but not integrated into the conceptual framework of the individual. In the book *Project 2061: Science for All Americans*, such knowledge is described as concepts without connections or links:

> “Concepts-the essential units of human thought-that do not have multiple links with how a student thinks about the world are not likely to be remembered or useful. Or, if they do remain in memory, they will be tucked away in a drawer labeled, say, "biology course, 1995," and will not be available to affect thoughts about any other aspect of the world. Concepts are learned best when they are encountered in a variety of contexts and expressed in a variety of ways, for that ensures that there are more opportunities for them to become imbedded in a student's knowledge system.”[10]

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[7] Perkins, D., “Smart Schools: Better Thinking and Learning for Every Child” New York: The Free Press, 1992, p. 21.

[8] Shapiro, I., Principal Investigator, “A Private Universe Project” Harvard-Smithsonian Center for Astrophysics, Science Education Department, Science Media Group. 1989.

[9] Perkins, D., “Smart Schools: Better Thinking and Learning for Every Child” New York: The Free Press, 1992, p. 22.

[10] American Association for the Advancement of Science, “Science for All Americans: Project 2061” New York: Oxford University Press, (1990), p. 198.

This is very similar to Perkins' concept of *ritual knowledge*[11], the use of particular rote skill, key phrases, or terms when confronted by a particular problem, without any real understanding. For example, a physics student may always associate the term acceleration with force, and even be able to produce the mathematical relationship between the two quantities without having any comprehension of what the terms mean or why the mathematical relationship exists.

Naïve knowledge or alternate conceptions. Perkins uses the term *naïve knowledge* to refer to the alternate conceptions of students, who even after considerable instruction retain their original beliefs. This is a result of not having their core intuitions or concepts challenged in the classroom. This can result from the failure of the curriculum to directly address the misconceptions or to view them as unworthy of consideration. But the existence of these misconceptions can have a real impact on the understanding of new material. This is reflected in the most recent standards for science education:

> "...to incorporate some new idea, learners must change the connections among the things they already know, or even discard some long-held beliefs about the world. The alternatives to the necessary restructuring are to distort the new information to fit their old ideas or to reject the new information entirely. Students come to school with their own ideas, some correct and some not, about almost every topic they are likely to encounter. If their intuition and misconceptions are ignored or dismissed out of hand, their original beliefs are likely to win out in the long run, even though they may give the test answers their teachers want."[12]

Posner[13] believes that all student learning occurs against the backdrop of the learner's current conceptual framework. Without such a framework, it would be impossible for learners to ask questions about the phenomena under study. This is in

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[11] Perkins, D., "Smart Schools: Better Thinking and Learning for Every Child" New York: The Free Press, 1992, p. 25.

[12] American Association for the Advancement of Science, "Science for All Americans: Project 2061" New York: Oxford University Press, (1990), p. 198.

direct contention with pure empiricism, which believes that learning comes through the senses without the need for prior concepts or frameworks. If the prior knowledge is in error, the potential for future learning is threatened:

> "The idea, however, that learning involves the linkage of information assumes that the prior knowledge is worth linking to. The cognitive science research indicates that if a learner harbors an incorrect or faulty concept about some phenomena (for example, the size of an object is directly related to how fast it moves in free fall), then any attempts to link new information to that faulty concept or to build a meaning network from that point of view are doomed to fail."[14]

When confronted with the dissonance between their internal frameworks and external reality, students are forced to create or construct models to address the disparity. If they do not make a change to the "faulty" conceptual framework, the new concepts will not be integrated into their thinking. Students may choose to a) create an entirely new model for the specific domain, or b) use or modify an existing theory or model. Posner notes that students in the classroom typically use existing models that are combined or modified to achieve the desired purpose and validity required. This new model must also be integrated into the students' existing framework of models and concepts. Throughout the process of model development, the validity and limits of the new model must be constantly scrutinized. Questions of correspondence, completeness, consistency (both internal and external), sensitivity, fidelity, and final outcome must all be utilized to refine and correct the model under development.

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[13] Posner, G.J., Strike, K.A., Hewson, P.W., & Gertzog, W.A., "Accommodation of a scientific conception: Toward a theory of conceptual change," Science Education 66(2), 211-227.

[14] Duschl, R., "Restructuring Science Education: The Importance of Theories and Their Development", New York: Teachers College Press, 1990, p. 99.

III. Sources of Alternate Conceptions

So, if our students' minds are filled with metaphors, concepts, and frameworks, were do they originate? The question is not a simple one to answer because it deals with issues that deal with both cognitive features and pedagogical practice.

Our experiences. Some of these conceptions are created and shaped by our participation in the real world. As a child we learn of our environment through our senses. Either by accident or through experimentation we learn that flames are hot (often to our discomfort), wood floats on water, helium balloons go up through the air, things do not disappear (conservation of matter), balls don't roll forever, and feathers float more slowly to the ground than do stones. This is by no means an exhaustive list; we learn a colossal number of these concepts early on, typically by the age of 3 or 4 when they become part of the cognitive framework that we use to understand our world. Experiences that create dissonance with our existing framework are startling, and at times, appear magical.

Experiments with infants show that, even before the age of 1, we have a *cognitive expectation* that matter must be conserved. Infants are shown a toy that is slid across a tabletop through a framework and then back out of the other side. The toy remains visible at every point during its travel. If the experimenters arrange the experiment so that the toy "disappears" while traveling through the framework, or if the toy "changes" after passing through the framework, the infant is visibly startled by the incongruity of the situation. It is no less startling for students in middle school to see a feather and a stone fall at the same rate in a vacuum. It violates all of their childhood experimentation and experiences. This is a magical experience that can be met with disbelief or temporary dissonance, resulting either in deep conceptual change or in a trivial bit of inert knowledge – "in the rare event of a vacuum, stones and feathers fall at the same rate." In either case the dissonance is resolved. The first case results in a fundamental change in the way that the student views the world, creating a more mature mental model by incorporating the concept of air resistance. In the second case, the student never recognizes the fact that *all* objects fall at the same rate without air resistance. The demonstration is not seen as reflecting reality, but only a scientific "trick" whose results must be known for the next test.

Would this student make a conceptual change if presented with a sufficient number of examples that contradicted their prior assumptions? Perhaps, but there also exists the possibility that each case would be seen as just another unique case. The student would never make the necessary generalization to see them as connected phenomena.

Language. George Lakoff and Mark Johnson in their book *Metaphors We Live By* identify metaphors as the primary tool of human thought. These metaphors are so ingrained in our language and perception as to be undetectable in normal experience. Metaphors (models) help us make sense of our new experiences (*target* domain) by mapping it to our familiar experience (*source* domain). Purely intellectual concepts, such as those found in science education, are often, if not always, based on metaphors that have a physical or cultural bias.[15] Concepts such as *force* are always associated (in common speech) with motion or change; it is anti-intuitive to think of force as being a static entity, and yet this is typical in cases of physical equilibrium. Since *force* is always related to action, students view inanimate objects as barriers to motion, but not agents of *force*. Students are willing to perceive a human hand holding a stationary ball as providing an upward force to balance the pull of gravity, but are unwilling to acknowledge the same upward force provided by a inanimate tabletop.

This relationship of force and action is reflected in the particular student misconceptions of Newton's laws. Equating force with motion leads to the belief that motion is impossible without a force or "actor". This is the basis for the Aristotelian belief in the principal of impetus – in which some quantity, in this case impetus, must be given the object to allow it to move. When the impetus "runs out" the object stops moving. In a similar manner the second law is assumed to state that every force produces an acceleration, which is only true if the net force is not zero. Finally, the third law is affected by the belief that the larger the object in a collision, the larger the force. When students are presented with a baseball hitting a bat, most will tell you that the ball applies a greater force on the ball than the ball applies to the bat.

David Hestenes notes that these common sense notions of reality are reflected in the *misplaced metaphors* that directly affect the learning of physics. In his work he notes the following antagonism between these naïve beliefs and the three Newtonian laws of motion[16]:

Newtonian Concept	***Vs.***	***Naïve Belief***
First Law - an object remains at rest or at a constant velocity unless acted upon by a net external force	Vs.	"Motion requires force" (Impetus principal)
Second Law - the acceleration of an object is equal to the net force applied divided by the object's mass	Vs.	"Force implies action" (There are no passive forces - all forces create acceleration)

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[15] Lakoff, G. & Johnson, M., "Metaphors We Live By" Chicago: University of Chicago Press, 1984, p. 19.

[16] Hestenes, D. (1996). "Modeling Methodology For Physics Teachers" 1996 Proceedings of the International Conference on Undergraduate Physics, College Park, p. 5.

Third Law - for every action there is an equal and opposite reaction	Vs .	"Force is War" (Dominance principal - the larger force always "wins")

He notes that these *misplaced metaphors*, although reasonably deep-seated, can be adjusted fairly easily to make sense of new phenomena. The modeling process discussed in section five of this paper demonstrates some techniques used by Hestenes to overcome these metaphors through modeling and mediated peer instruction.

A curriculum of "truths". David Perkins relates the story of mathematical alternate conceptions in a group of adult conference participants[17]. After presenting a lecture on misconceptions in mathematics and science students where he noted that the equation $\sqrt{a^2+b^2}=a+b$ is incorrect, two individuals from the audience approached him and asked why the equation was wrong. They could not believe that such a simple and eloquent equation should be incorrect. Perkins knew from his experience as a mathematician and educator that corrrect relationships in mathematics are "hard won." Most nice looking equations turn out to be false; only the extensive apparatus of the mathematical proof is able to filter true equations from the chaft. These individuals had never experienced the search for true equations. They were always provided with the correct and finished equations by way of their textbooks and teachers. He says of his questioners:

> "They had no exposure to building mathematical systems. They had learned mostly the received content of mathematics, the many beautiful relationships that *do* hold up. From this kind of experience, it is very natural to conclude that nice-looking relationships generally work out, to expect validity, and to react with surprise when a nice-looking relationship betrays that expectation."[18]

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[17] Perkins, D., "Smart Schools: Better Thinking and Learning for Every Child" New York: The Free Press, 1992, p. 73.

[18] Perkins, D., "Smart Schools: Better Thinking and Learning for Every Child" New York: The Free Press, 1992, p. 74.

This is a form of *reductionism* – to reduce all ideas and concepts down to their smallest, easiest to comprehend, and most efficient state. In our attempt to reduce the key concepts of a subject down to easily grasped ideas, we often oversimplify the material, to the disservice of our students. We limited their views of a subject because of our fear that they will be overwhelmed by the exposure to the entire, and sometimes, inelegant truth. Teachers must strive against the natural desire to keep student explorations within the comfortable, concrete realm. In physics a majority of the textbooks present Newton's laws to the students without the historical struggles or messy inductive reasoning behind them. This can be rectified to some extent by a Constructivist classroom where students are forced to build constructs for their new knowledge, but it is not a complete solution. Students need to see the "wholeness" of a thought process. It is therefore a primary responsibility of the teacher to present the alternate, and often conceptually ugly, story to their students in an attempt to have them share the conceptual struggles that others have faced.

Richard Duschl in his book *Restructuring Science Education* warns of the consequences of this kind of selective curriculum. Students spend their time in most physics courses justifying existing knowledge rather than learning the process of discovering knowledge. They are not given the opportunity to explore the development of a theory or the many missteps leading to our current theory. This type of instruction is described as being *epistemologically flat*[19], that is, without the full logical development of the idea. Students perceive only the end product without seeing the processes leading to

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[19] Kliborn, B., World views and science teaching. In H. Munby, G. Orpwood, & T. Russell (eds.), "Seeing curriculum in a new light." Essays from science education, Toronto: OISE Press, 1980.

its development. Without the linkages to historical events and people, discoveries such as Newton's Laws appear as singularly remarkable events that are unlikely to be linked to other mental constructs, thus resulting in additional inert knowledge. More importantly, Newton's Laws are less likely to threaten any alternate conceptions the students might hold. If students do not connect their alternate conceptions with those of Aristotle or the concepts of impetus, they are not likely to see Newton's Laws as a menace to their current belief system. These alternate frameworks, once established, are very difficult to modify. Brown and Clement[20] found that college physics students were fairly confident of their incorrect answers on a set of qualitative answers on Newton's Third Law even after completing a course in high school physics.

IV. Identifying Alternate Conceptions

The first step in overcoming students' alternative conceptions must be to identify them. A majority of the misconceptions are the direct result of our language and experiences as noted in the previous section. These common misconceptions occur to some extent in all entering physics students, and thus, an effective curriculum should incorporate techniques to directly address these conceptions.

Common Student Conceptions. The Comprehensive Conceptual Curriculum for Physics (C^3P) project has undertaken the task of cataloging common student misconceptions. The purpose of this list is to aid physics teachers in designing instructional activities and conceptual models that help students examine and overcome

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[20] Brown, D. & Clement, J. , " Misconceptions concerning Newton's law of action and reaction.," Proceedings of the second international seminar on misconceptions and educational strategies in science and mathematics. Ithica, NY: Cornell University. 1987

their alternate conceptions. The following list is a small section[21] that relates to common student misconception regarding Newton's laws:

NEWTON'S LAWS[22]:

- Action-reaction forces act on the same body.
- There is no connection between Newton's Laws and kinematics.
- The product of mass and acceleration, ma, is a force.
- Fiction can't act in the direction of motion.
- The normal force on an object is equal to the weight of the object by the 3rd law.
- The normal force on an object always equals the weight of the object.
- Equilibrium means that all the forces on an object are equal.
- Equilibrium is a consequence of the 3rd law.
- Only animate things (people, animals) exert forces; passive ones (tables, floors) do not exert forces.
- Once an object is moving, heavier objects push more than lighter ones.
- Newton's 3rd law can be overcome by motion (such as by a jerking motion).
- A force applied by, say a hand, still acts on an object after the object leaves the hand.

The list helps the teacher guide the students into self-awareness of the misconceptions that they may possess, and by acknowledging them, the students have a greater chance of overcoming them.

Diagnostic Tests. If self-awareness of our alternate conceptions help overcome their prejudice, it is important to offer physics teachers an instrument to aid their students in such self diagnosis. Halloun and Hestenes have developed just such a series of diagnostic tests to measure the extent of student held alternate conceptions. These tests, the Mechanics Baseline Test (MBT) and the Force Concept Inventory (FCI)[23] are instruments that measure the extent of student alternate conceptions within the physics curriculum. They note in their study:

> "A low score on the physics diagnostic test does not mean simply that basic concepts on Newtonian mechanics are missing; it means that alternative misconceptions about physics are firmly in place. If such misconceptions are not corrected early in the course, the

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[21] The complete list of student misconceptions can be found in Appendix 3.

[22] Comprehensive Conceptual Curriculum for Physics List of Student Misconceptions. Available on-line: http://phys.udallas.edu/altconcp.html, section on Newton's Laws.

[23] Hestenes, D., Wells, M., & Swackhamer, G., "Force Concept Inventory," The Physics Teacher, 30:141-158 (1992).

> student will not only fail to understand much of the material, but worse, he is likely to dress up his misconceptions in scientific jargon, giving the false impression that he has learned something about science."[24]

The FCI tests students' ability to overcome naïve beliefs in six fundamental aspects of the Newtonian force concept. The tests can also be used to measure student alternate conceptions before and after instruction, thus providing the ability to assess the success of various instructional techniques. Comparing traditional lecture methods abilities to overcome alternate conceptions, Hake has discovered that students in traditional classrooms typically show a mean gain of 22% on the FCI, while students exposed to non-traditional methods, such as the Modeling method described in the next section, show a mean gain of 52%.[25]

The following is an example question from an early version of the FCI:

4. 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.

This question attempts to measure the common student misconception that the larger object produces the larger force during a collision. If the students still possess this conception, they will choose either answer *a* or *d*, depending on the nature of their misconception. The teacher and the student can use the results of the FCI to identify the types of alternate conceptions that need to be addressed within the course. The current

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[24] I. A. Halloun and D. Hestenes, "The initial knowledge state of college physics students", Am. J. Phys. **53**, 1048 (1985).

[25] Hake, R., "Interactive-engagement vs. traditional methods: A six-thousand-student survey of mechanics test data for introductory physics course" Am. J. Physics (submitted)

FCI has 30 questions that measure the extent of student misconception in a variety of situations.

V. Overcoming Alternate Conceptions

Identifying alternative conceptions is not enough. For change to occur there must exist a cognitive dissonance between student's internal framework of concepts and the perceived world. The dissonance can be the result of external contradictions or by exposing internal incongruities in the conceptual framework. This dissonance can result in a mild change in the student's conceptual models or a radical restructuring of the entire framework. Posner identifies these changes as *assimilation* when students use existing concepts to deal with new phenomena and *accommodation* when student conceptions are inadequate to deal with a new phenomenon at which point the student must replace or modify their central conceptual framework.[26].

Restructuring a conceptual framework is always an inherently "risky" activity for the student. Change is often threatening to the student who would rather maintain the comfortable rote skills than risk change to a potentially risky new model. It is important to build a sense of trust and resiliency within the classroom. Often a student feels that an alternate concept is wrong. It is important to note that many commonly held misconceptions were considered to be true for many centuries and our current concepts of "truth" may also be questioned in the next century. It is important to see conceptual change as a necessary and dynamic process.

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[26] Posner, G. C., Strike, K. A., Hewson, P. W., & Gertzog, W. A., "Accommodation of Scientific Conception: Towards a Theory of Conceptual Change" Science Education 66(2), p. 212.

Bridging Analogies. Some of the memorable lessons in physics revolve around the use of effective analogies or models. Hans Christian von Baeyer, a science writer, defines an analogy as a device that gives verbal access to the subtle and difficult. There are many analogies in physics used to describe the most difficult concepts to understand. Analogies have the potential to overcome alternate concepts by appealing directly to the source of the student's misunderstanding. One of the most famous analogies was created by Albert Einstein to help explain his theories in the esoteric field of General Relativity to the general public without immensely difficult mathematics.

In the analogy, Einstein describes the effect of gravity as being identical in every way to what is experienced by a rider in an ever-accelerating elevator located in space. The rider would be continually pressed to the floor by what appeared to be "gravity" and all experiments carried out by the rider to measure this "gravity" would give the same results as if they were performed on the Earth's surface. This analogy is of itself is not extraordinary, but it does allow an extraordinary prediction. If the rider shines a flashlight across the accelerating elevator, the motion of the elevator will cause the beam of light to strike the opposite wall of the elevator slightly below the level of the flashlight. This is due to the elevator wall's forward motion during the time that it takes the flashlight's beam to reach the far wall. Thus, the light beam appears to "bend" slightly towards the floor during the beam's travel. If we believe that the analogy is a valid model of reality, then a beam of light should also be "bent" by the Earth's gravity – which is a completely unexpected but genuine result.

In his essay, von Baeyer suggests the steps for creating useful analogies:

> "First, state the problem. It should be important, of universal concern, and genuinely incomprehensible, for good analogies should not traffic with the frivolous or the obvious. Next,

> introduce a familiar object or everyday activity that is instantly recognizable; describing one mystery in terms of another is a waste of time. If, in the third step, you can lead a reader to see the relationship between the incomprehensible concept and its simple analogy, you have succeeded. But good analogies go one step further. By logical extension, they lead to something beyond what they were supposed to explain, to a prediction or an unexpected discovery, to something so surprising that it fixes the story in the reader's mind."[27]

The predictive ability of a good analogy allows the user to understand the nature of a difficult problem and to produce potential solutions to intractable problems.

It would seem that these types of analogies could also be used to overcome alternate conceptions in students, but direct analogies often fail in practice. John Clement[28] attempted to use analogies to overcome the notion that an inanimate tabletop cannot provide an upward force on a book sitting on its surface. In his experiment, he draws an analogy between the tabletop and a spring and then asks the students if a hand pushing down on a spring is analogous to the book pushing down on the table. The results show that most students are unwilling to compare the tabletop and the spring because the students do not see the two objects as being physically similar. Clement's solution to this problem was to use a series of bridging analogies between what the students accepted (hand on the spring) toward the unacceptable (book on the tabletop). He first showed the book on a piece of foam that flexed with the book on top, similar to what the spring would do, then he moved the book onto a thin piece of plywood which also bent, but this time, the students were willing to acknowledge that the piece of plywood was acting like a spring. Finally he placed the book on the tabletop and asked the students if the case was similar, most agreed, although some required proof that the tabletop "bent." This proof was provided by reflecting a beam of light off of a small

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[27] Von Baeyer, H. C. & Rapoport, B., "Fermi Solutions; Essays on Science" New York: Random House, 1994, p. 121.

[28] Clement, J., "Using bridging analogies and Anchoring Intuitions to Deal with Students' Preconceptions in Physics," Journal of Research in Science Teaching, 30(10), 1241-1257. (1993)

mirror placed on the table – when the book was placed on the table, the table flexed and the reflected light beam moved. The students moved from what was known, which Clement refers to as an *anchoring analogy*, to eventually counter their alternate conceptions.

When teaching students to use analogies effectively, we must also be aware of the inexperienced problem solvers' use of inappropriate analogies. The work of Stavy and Tirosh[29] suggests that inexperienced solvers tend to represent a given problem according to surface or visible features, whereas experienced solvers utilize the scientific principals underlying the problem. E. David Wong adds that all constructed analogies are faulty to some extent. They do not completely or appropriately map what is known to the problem under consideration. To counter this problem, the learner must a) deliberately evaluate their own analogies by identifying both similarities and differences between the two domains, and b) construct *multiple* analogies to counter any weaknesses of a single model[30].

Modeling Instruction. Ibrahim Halloun and David Hestenes of Arizona State University have proposed the use of modeling to correct many weaknesses of the traditional lecture-demonstration method, including the fragmentation of knowledge, student passivity, and the persistence of naive beliefs about the physical world[31]. Their work suggests that effective science teaching should account explicitly for students' initial knowledge state, and refrain themselves from the mere transfer of scientific information. They acknowledge that existing conceptual frameworks can inhibit learning

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[29] Stavy, R. & Tirosh, D., "When analogy is perceived as such", Journal of Research in Science Teaching **30**, 1237 (1993).

[30] Wong, E.D., "Understanding the generative capacity of analogies as a tool for explanation", Journal of Research in Science Teaching **30**, 1262 (1993).

if students are not forced to resolve conflicts that exist between the models that they are presented and their internal frameworks. The instructional model notes that the understanding is not a simple commodity that can be easily transferred from the teacher to the student. Physics education is currently taught in an episodic manner with little time set aside to make connections between various physics concepts or the development of schematic models[32]. Without the conscious effort to take the time to have students examine their beliefs and make the necessary connections, students will retain their alternate conceptions without significant change.

Instruction is organized into *modeling cycles* which engage students in all phases of model development, evaluation and application in concrete situations -- thus promoting an integrated understanding of modeling processes and acquisition of coordinated modeling skills. The teacher sets the stage for student activities, typically with a demonstration and class discussion to establish common understanding of a question to be asked of nature. Then, in small groups, students *collaborate* in planning and conducting experiments to answer or clarify the question. Students are required to present and justify their conclusions in oral and/or written form, including a *formulation* of models for the phenomena in question and *evaluation* of the models by comparison with data. Technical terms and representational tools are introduced by the teacher as they are needed to sharpen models, facilitate modeling activities and improve the quality of discourse. The teacher is prepared with a definite agenda for student progress and *guides* student inquiry and discussion in that direction with Socratic questioning and

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[31] Hestenes, D. (1996). "Modeling Methodology For Physics Teachers" 1996 Proceedings of the International Conference on Undergraduate Physics, College Park, p. 6.

[32] I. Halloun, "Schematic Concepts for Schematic Models of the Real World: The Newtonian Notion of Force" Science Education, Manuscript No. 6052, Draft II, Jan. 5 1997. (unpublished), p. 4.

remarks. The teacher is equipped with a *taxonomy* of typical student misconceptions to be addressed as students are induced to articulate, analyze and justify their personal beliefs.[33]

The implementation of the Modeling approach requires both the selection and design of paradigm problems for intensive study, and a Socratic teaching style.[34] Paradigm problems are chosen to be characteristic of the entire domain under study and their solutions are used as models for the solution of other problems in the domain. These problems must first evoke and challenge the alternate conceptions held by students. Secondly these problems must require for their solution the complete system of modeling techniques that are to be taught[35]. It is important in this strategy to choose as few paradigm problems possible to cover the material. This allows the students adequate time to study and understand the significance of each solution and its relationship to other potential problems. It also gives them time to recognize and resolve the conflict between the solutions and their alternative frameworks. Finally, paradigm problems should motivate students by incorporating situations that are relevant to everyday life.

Historical Perspective. Richard Duschl in his book *Restructuring Science Education* emphasizes the fact that over the past 30 years science education has focused on a curriculum for future scientists. The curriculum focuses on the justification of current knowledge rather than tracing its epistemological background -- how we have come to be at the particular point in our understanding of a concept. This has produced a

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[33] Hestenes, D. (1996). "Modeling Methodology For Physics Teachers" 1996 Proceedings of the International Conference on Undergraduate Physics, College Park, p. 6.

[34] I. A. Halloun and D. Hestenes, "Modeling Instruction in Mechanics", Am. J. Phys. **55**, 455 (1987).

[35] See Appendix 1 for a complete list of paradigm problem characteristics

curriculum that has ignored the creative, often chaotic, development of scientific models and focused instead on the re-verification of current theory.

The first type of curriculum, scientific-knowledge teaching, presents students with the final form of a theory or law; in essence the "absolute truth." This echoes the problems of teaching only correct equations mentioned in Perkins' discussion of mathematics. Science is reported as a sequence of logical ideas whose fruition is our modern theories and laws. In reality, science is rarely as simple or as linear as the reporting of the historical process would indicate. Scientific discovery is not always logical and theories are not always correct. This type of curriculum focuses on the testing of knowledge activities. Scientific knowledge – hypotheses, principles, and theories -- are learned on the basis of their contribution to the established or final form of knowledge. Scientific theories are presented in a declarative, rather than procedural, manner.

Duschl suggests that we move to a curriculum that he refers to as *knowledge about science*, which focuses on reporting on how scientific discoveries are made. It allows the student to see both the knowledge of why science believes what it does and also, how science has come to think that way. Knowledge about science curriculum includes the various false starts, modification of concepts, provisional and finished forms of knowledge, and the reasoning employed in the pursuit of understanding. Scientific theories are not treated as simple definitions within an ordinary curriculum, but as a tentative hypothesis based on observations and current understanding. It attempts to build an epistemological framework and conceptual basis for our current knowledge through the study of the processes by which the discoveries were made. Scientific discovery must be seen as dynamic; without the fundamental concept of change, students understand the final products of inquiry, but do not learn the process of inquiry. They become willing to accept current theory without question and tend to ignore the rational standing of current theory.

The knowledge about science curriculum purposed also incorporates historical, political, and social issues to understand the process of scientific change. It is impossible to discuss the change in scientific theories without considering the society at the time. This provides the student a richer tableau of understanding, connecting many different aspects of knowledge to understand the context for change. For example, it is impossible to fully understand the enduring quality of Ptolemy's concept of planets orbiting in circular paths unless you understand the Greek ideal of perfection, the decline of the Roman Empire, and the rise of Christianity. The richness inherent in such a discussion of the societal influence in the development of a scientific principle cannot be underestimated.

This curriculum encourages critical thought in the examination of past theories through critical analysis. Students are forced to test their own hypotheses and determine the validity of each theory. If a theory fails this test, they are forced to create a new hypothesis that fits their observations. Because students are testing and creating the new theories, they are more likely to internalize the results of their efforts. This parallels a Constructivist dictum of discovery – the students discover the "truth" on their own and are more likely to retain it. These ideas are incorporated into the latest standards for science education, which urges:

> "Students can develop a sense of how science really happens by learning something of the growth of scientific ideas, of the twists and turns on the way to our current understanding of such ideas, of

> the roles played by different investigators and commentators, and of the interplay between evidence and theory over time."[36]

Students must be made aware of the dynamic nature of the scientific process. A curriculum must incorporate a selection of the historical and philosophical background of earlier discoveries. This might take the form of readings or student research into earlier forms of our current knowledge. Students might be able to form graphical knowledge trees that illustrate the development of a theory. Ideally, the students would be able to use this background knowledge to form testable predictions that would validate or eradicate earlier theories and concepts. Some of the theories that they investigate may lead nowhere; some would argue that this is a waste of the students' time – but this is a true reflection of the actual nature of science and it gives the students a deep understanding of this process.

These predictions should lead to testable hypotheses. Students should be able to use their hypotheses to design their own age-appropriate experiments to test the theory. By designing and testing their own concepts they are more likely to incorporate more sophisticated theories into their own understanding. These discontinuities can provide the impetus for a radical restructuring of the students' knowledge framework.

VI. Conclusion

Our ultimate goal as educators must be the desire for our students to truly *understand* physics concepts. This is a difficult proposition because we can only measure understanding indirectly by the types of the performances that we arrange for our students. We will never be able to directly assess students' mental schemata; we must

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[36] American Association for the Advancement of Science, "Science for All Americans: Project 2061" New

rely on imperfect techniques that attempt to discern the mental concepts that they use to view the world. The techniques presented in this paper attempt to address potential means to make associations with the underlying framework of students conceptions as a means of identifying and promoting change in alternate conceptions.

Perkins notes in his work that the teacher's most important choice is to decide what to teach. To overcome student misconceptions requires the teacher to make a dedicated choice to spend the time and effort to overcome existing student misconceptions. Traditional education has ignored this problem with the result that our graduates maintain their misconceptions well beyond the physics classroom. If we are to achieve understanding, which is the goal of true learning, we must be willing to sacrifice some breadth to obtain the necessary depth of treatment. Unfortunately, many teachers find themselves constrained by external pressures to cover all the material in the book. These pressures, which include parental expectations and standardized tests, are not simple hurdles to overcome, but required to make our schools into reflective and thoughtful places of learning.

The techniques cited in this paper have the potential to be applied to other disciplines as well. Physics is not the only discipline in which students can achieve success with only a cursory understanding of the material. Restructuring the curriculum of all courses to include the historical and logical development of ideas, analogies to aid understanding, and modeling of effective learning has the potential to reshape the educational landscape of our schools.

York: Oxford University Press, (1990), p. 201.

Appendix 1: Characteristics of Paradigm Problems

1. A paradigm problem is not a straightforward numerical application *offormulas.*
2. The problem describes a real world situation with physical objects. In order to reinforce the universality of models, and hence of physics theories, different problems that can be solved using the same model should be presented that involve different contexts, or objects of different scale (from common ones in everyday life to microscopic or astronomical ones).
3. The problem involves some *composite* system (made out of at least two interacting objects), or more than one *simple* system.
4. The problem does not suggest explicitly the appropriate model for each object/event.
5.* Different objects may undergo events of different types (e.g. translation in one or two dimensions, and/or rotation), and hence require models from different families.
6.* Construction of at least one new emergent model is required, out of familiar ones.
7.* A model can be constructed out of the *givens* without the *Question(s).*
8.* The problem contains superfluous information.
9. The problem contains constraints, limits or boundary conditions.
10.* Some required information is not provided (aside from familiar constants, like *g*, such as the direction of motion, in an Atwood machine, or the direction of current in an electric circuit.
11. Model composition includes descriptors of different types: e.g. descriptive (kinematics) and explanatory (dynamics).
12. Model structure requires a non-straightforward choice of appropriate laws or the use of many laws (e.g., Newton's laws and W-E Theorem). As in (2), and in order to foster the unification of physical theories, questions are included that require generic laws like the superposition principle, and conservation laws.
13. Model construction involves multiple mathematical representations that need to be extrapolated and coordinated: e.g., diagrams, graphs and equations. However, mathematical operations should be kept at a minimum. Numerical calculations should not be tedious, and should have a conceptual purpose if required (e.g., to establish correspondence to the real world, and facilitate extrapolation of results).
14.* Questions do not specify explicitly concepts that need be evaluated (e.g. it is better to *ask where* two objects *meet* than to ask for the common *position* at the meeting time).
15.* Questions ask for a comparison of objects with respect to a specific property (preferably not stated explicitly) rather than for an evaluation of this property for each object separately (e.g., it is better to ask *"how would two objects see each other moving ?* " than to ask for the velocity/acceleration of each).
16. Follow-up questions are included that ask for real world interpretations, and that help to resolve common misconceptions.
17. Follow-up questions are included that ask for results extrapolation (e.g., predict what happens if something changes in the situation, or if we look at the same situation in a different reference system).

* A characteristic of a higher order paradigm problem[37]

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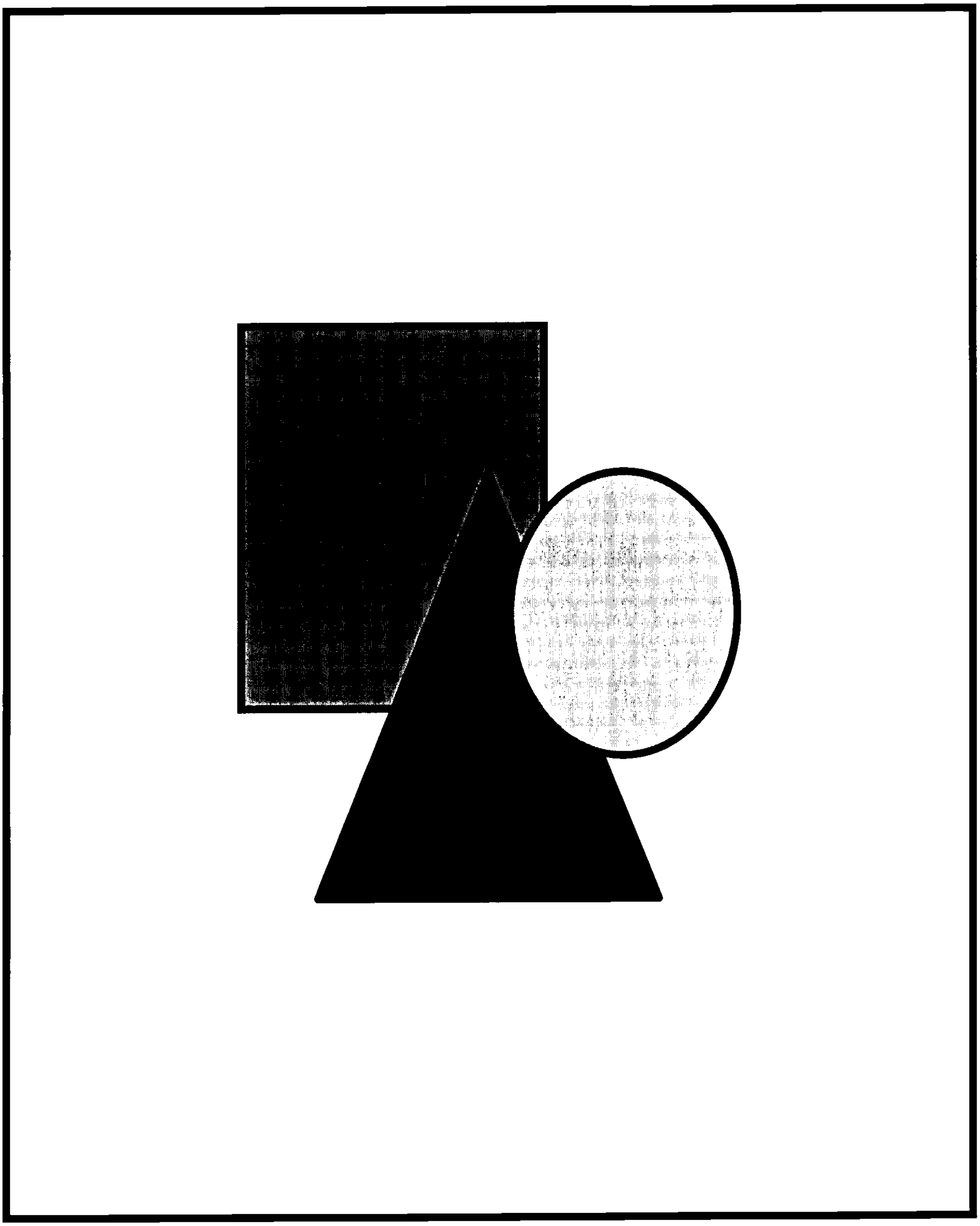
[37] I. Halloun, "Schematic Concepts for Schematic Models of the Real World: The Newtonian Notion of Force" Science Education Manuscript No. 6052, Draft II, Jan. 5 1997. (unpublished)

Appendix 2: Flow Chart Illustrating Student Modeling of New Constructs



Appendix 3: Common Student Misconceptions[38]

0. OVERALL/KINEMATICS

History has no place in science.
Two objects side by side must have the same speed.
Acceleration and velocity are always in the same direction.
Velocity is a force.
If velocity is zero, then acceleration must be zero too.

1. FALLING BODIES

Heavier objects fall faster than light ones.
Acceleration is the same as velocity.
The acceleration of a falling object depends upon its mass.
Freely falling bodies can only move downward.
There is no gravity in a vacuum.
Gravity only acts on things when they are falling.

2. INERTIA

Forces are required for motion with constant velocity.
Inertia deals with the state of motion (at rest or in motion).
All objects can be moved with equal ease in the absence of gravity.
All objects eventually stop moving when the force is removed.
Inertia is the force that keeps objects in motion.
If two objects are both at rest, they have the same amount of inertia.
Velocity is absolute and not dependent on the frame of reference.

3. NEWTON'S LAWS

Action-reaction forces act on the same body.
There is no connection between Newton's Laws and kinematics.
The product of mass and acceleration, ma, is a force.
Fiction can't act in the direction of motion.
The normal force on an object is equal to the weight of the object by the 3rd law.
The normal force on an object always equals the weight of the object.
Equilibrium means that all the forces on an object are equal.
Equilibrium is a consequence of the 3rd law.
Only animate things (people, animals) exert forces; passive ones (tables, floors) do not exert forces.
Once an object is moving, heavier objects push more than lighter ones.
Newton's 3rd law can be overcome by motion (such as by a jerking motion).
A force applied by, say a hand, still acts on an object after the object leaves the hand.

4. GRAVITATION

The Moon is not falling.
The Moon is not in free fall.
The force that acts on apple is not the same as the force that acts on the Moon.
The gravitational force is the same on all falling bodies.
There are no gravitational forces in space.
The gravitational force acting on the Space Shuttle is nearly zero.
The gravitational force acts on one mass at a time.

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[38] Comprehensive Conceptual Curriculum for Physics List of Student Misconceptions. Available on-line: http://phys.udallas.edu/altconcp.html

Moon stays in orbit because the gravitational force on it is balanced by the centrifugal force acting on it.
Weightlessness means there is no gravity.
The Earth's spinning motion causes gravity.

5. CONSERVATION OF ENERGY
Energy gets used up or runs out.
Something not moving can't have any energy.
A force acting on an object does work even if the objects does not move.
Energy is destroyed in transformations from one type to another.
Energy can be recycled.
Gravitational potential energy is the only type of potential energy.
When an object is released to fall, the gravitational potential energy immediately becomes all kinetic energy.
Energy is not related to Newton's laws.
Energy is a force.

6. CONSERVATION OF MOMENTUM
Momentum is not a vector.
Conservation of momentum applies only to collisions.
Momentum is the same as force.
Moving masses in the absence of gravity do not have momentum.
The center of mass of an object must be inside the object.
Center of mass is always the same as the center of gravity.
Momentum is not conserved in collisions with "immovable" objects
Momentum and kinetic energy are the same.

7. CIRCULAR MOTION
Circular motion does not require a force.
Centrifugal forces are real.
An object moving in circle with constant speed has no acceleration.
An object moving in a circle will continue in circular motion when released.
An object is circular motion will fly out radially when released.

8. ANGULAR MOMENTUM
Any force acting on an object will produce a torque.
Objects moving in a straight line can not have angular momentum.
Torque is the same as force and is in same direction.
Angular momentum is not a vector.
The direction of angular momentum is in direction of linear momentum.

9. KEPLER'S LAWS
Planetary orbits are circles.
The speed of a planet in orbit never changes.
An object must be at both foci of an elliptical orbit.
All the planets move in their orbits with the same speed.
No work is done on orbiting planets by the sun.
The orbits of the planets lie precisely in the same plane.
All the planets revolve about sun with the same period.
Revolution is the same as rotation.

10. NAVIGATING IN SPACE
Spacecraft travel in straight lines from one planet to another.
Spacecraft can be launched anytime to travel from one planet to another.
Spacecraft are not affected by the sun.
Motion relative to Earth is same as motion relative to the sun.
Jets can fly in space.
Spacecraft in orbit about Earth don't follow a sinusoidal path relative to the sun.
Rockets need something (air) to push against.

11. CURVED SPACE & BLACK HOLES

Space is not something.

Black holes are big.

Light always travels in straight lines.

Black holes exert a greater gravitational force on distant objects than the star from which it was formed.

Observations made in a gravitational field are different that those made in a system undergoing constant acceleration.

Things in space make sounds.

If the Sun were to become a black hole, the Earth would get sucked into it.

12. TEMPERATURE AND GAS LAWS

A cold body contains no heat.

There is no limit on the lowest temperature.

At absolute zero motion of every part of an object stops.

An object has no mass at absolute zero.

Sweaters will make you warmer.

Cold can flow.

Gases can be compressed to zero volume.

Heat and temperature are the same thing.

Heat and cold flow like liquids.

Pressure is the same as force.

Skin is a good thermometer.

13. HARMONIC MOTION

The period of oscillation depends on the amplitude.

The restoring force is constant at all points in the oscillation.

The heavier a pendulum bob, the shorter its period.

All pendulum motion is perfect simple harmonic motion, for any initial angle.

Harmonic oscillators go forever.

A pendulum accelerates through lowest point of its swing.

Amplitude of oscillations is measured peak-to-peak.

The acceleration is zero at the end points of the motion of a pendulum.

14. WAVES

Waves transport matter.

There must be a medium for a wave to travel through.

Waves do not have energy.

All waves travel the same way.

Frequency is connected to loudness for all amplitudes.

Big waves travel faster than small waves in the same medium.

Different colors of light are different types of waves.

Pitch is related to intensity.

15. WAVE NATURE OF LIGHT

Light just is and has no origin.

Light is a particle.

Light is a mixture of particles and waves.

Light waves and radio waves are not the same thing.

In refraction, the characteristics of light change.

The speed of light never changes.

Rays and wave fronts are the same thing.

There is no interaction between light and matter.

The addition of all colors of light yields black.

Double slit interference shows light wave crest and troughs.

Light exits in the crest of a wave and dark in the trough.

In refraction, the frequency (color) of light changes.

Refraction is the bending of waves.

16. MICHELSON-MORLEY EXPERIMENT
    A null result means experiment was a failure.
    The aether exists because something must transmit light.
    Relativistic effects (length contraction) is the reason why no difference in the speed of light was observed.

17. SPECIAL RELATIVITY
    Velocities for light are additive like for particles.
    Postulates cannot be used to develop a theory.
    Length, mass, and time changes are just apparent.
    Time is absolute.
    Length and time only change for one observer.
    Time dilation refers to 2 clocks in 2 different frames.
    Time dilation and length contractions have not been proven in experiments.
    There exits a preferred frame of reference in the universe.
    A mass moving at the speed of light becomes energy.
    Mass is absolute, that is, it has the same value in all reference frames.

18. ELECTRIC FIELDS AND FORCES
    A moving charge will always follow a field line as it accelerates.
    If a charge is not on a field line, it feels no force.
    Field lines are real.
    Coulomb's law applies to charge systems consisting of something other than point charges.
    A charged body has only one type of charge.
    The electric field and force are the same thing and in the same direction.
    Field lines can begin/end anywhere.
    There are a finite number of field lines.
    Fields don't exist unless there is something to detect them.
    Forces at a point exist without a charge there.
    Field lines are paths of a charges motion.
    The electric force is the same as the gravitational force.
    Field lines actually radiate from positive to negative charges and convey motion.
    Field lines exist only in two dimensions.

20. MILLIKAN EXPERIMENT
    Charge is continuous and can occur any amount.
    An electron is pure negative charge with no mass.
    Oil drops are electrons.
    The scientific method is pure and absolute.
    Scientists always stumble on discoveries.
    Millikan measured the mass of the electron.

21. EQUIPOTENTIALS AND FIELDS
    Voltage flows through a circuit.
    There is no connection between voltage and electric field.
    Voltage is energy.
    Equipotential means equal field or uniform field.
    High voltage by itself is dangerous.
    It takes work to move a real charge on an equipotential.
    Charges move by themselves.
    Sparks occur when an electric field pulls charges apart.

22. POTENTIAL DIFFERENCE AND CAPACITANCE
    A capacitor and a battery operate on the same principle.
    A potential difference is only on plates of a capacitor and not in region between.
    Charge flows through a dielectric, such as glass.
    Designations of (+) and (-) are absolute.
    Q = CV is a basic conceptual law.
    No work is required to charge a capacitor.

A capacitor requires two separate pieces.
There is a net charge on a capacitor.
The capacitance of a capacitor depends on the amount of charge.
A positive charged capacitor plate only has positive charges on it.
Charges flow through a capacitor.

23. SIMPLE DC CIRCUITS

Resistors consume charge.
Electrons move quickly (near the speed of light) through a circuit.
Charges slow down as they go through a resistor.
Current is the same thing as voltage.
There is no current between the terminals of a battery.
The bigger the container, the larger the resistance.
A circuit does not have form a closed loop for current to flow.
Current gets "used up" as it flows through a circuit.
A conductor has no resistance.
The resistance of a parallel combination is larger than the largest resistance.
Current is an excess charge.
Charges that flow in circuit are from the battery.
The bigger the battery, the more voltage.
Power and energy are the same thing.
Batteries create energy out of nothing.

24. MAGNETIC FIELDS

North and south magnetic poles are the same as positive and negative charges.
Magnetic field lines start at one pole and end at the other.
Poles can be isolated.
Flux is the same as field lines.
Flux is actually the flow of the magnetic field.
Magnetic fields are the same as electric fields.
Charges at rest can experience magnetic forces.
Magnetic fields from magnets are not caused by moving charges.
Magnetic fields are not 3-dimensional.
Magnetic field lines hold you on the Earth.
Charges, when released, will move toward the poles of a magnet.

25. ELECTROMAGNETIC INDUCTION

Generating electricity requires no work.
When generating electricity only the magnet can move.
Voltage can only be induced in a closed circuit.
Magnetic flux, rather than change of magnetic flux, causes an induced emf.
All electric fields must start on (+) and end on (-) charges.
Water in dams causes electricity.

26. ALTERNATING CURRENT

Charges move all the way around a circuit and all the way back.
Voltage and current remain constant as in DC circuits.
Energy is not lost in a transformer.
A step-up transformer gives you something more for less input.
Transformers can be used to change DC voltages.
Electrical companies supply the electrons for your household current.

27. WAVE-PARTICLE DUALITY

Light is one or the other--a particle or a wave--only.
Light can be a particle at one point in time and a wave at another point in time.
Particles can't have wave properties.
Waves can't have particle properties.
The position of a particle always can be exactly known.

A photon is a particle with a wave inside.
Photons of higher frequency are bigger than photons of lower frequency.
All photons have the same energy.
Intensity means that the amplitude of a photon is bigger.
The Uncertainty Principle results from the limits of measuring devices.
Laser beams are always visible by themselves.
Sometimes you feel like a wave, sometimes you don't.

28. MODELS OF THE ATOM

There is only one correct model of the atom.
Electrons in an atom orbit nuclei like planets orbit the sun.
Electron clouds are pictures of orbits.
Electrons can be in any orbit they wish.
Hydrogen is a typical atom.
The wave function describes the trajectory of a electron.
Electrons are physically larger than protons.
Electrons and protons are the only fundamental particles.
Physicists currently have the "right" model of the atom.
Atoms can disappear (decay).

Appendix 4: Synopsis of the Modeling Method[39]

The Modeling Method aims to correct many weaknesses of the traditional lecture-demonstration method, including the fragmentation of knowledge, student passivity, and the persistence of naive beliefs about the physical world.

What to teach: Model-centered instructional objectives

To engage students in understanding the physical world by ***constructing and using scientific models*** to describe, to explain, to predict, to design and control physical phenomena.

- To provide students with ***basic conceptual tools*** for modeling physical objects and processes, especially mathematical, graphical and diagrammatic representations.

- To familiarize students with a small set of basic models as the ***content core*** of physics.

- To develop insight into the ***structure*** of scientific knowledge by examining how *models* **fit** into *theories.*

- To show how scientific knowledge is ***validated*** by engaging students in *evaluating* scientific models through comparison with empirical data.

To develop skill in all aspects of modeling as the ***procedural core*** of scientific knowledge.

How to teach: Student-centered instructional design

Instruction is organized into ***modeling cycles*** which engage students in all phases of model development, evaluation and application in concrete situations - thus promoting an integrated understanding of modeling processes and acquisition of coordinated modeling skills.

- The teacher sets the stage for student activities, typically with a demonstration and class discussion to establish common understanding of a question to be asked of nature. Then, in small groups, students ***collaborate*** in planning and conducting experiments to answer or clarify the question.

- Students are required to present and justify their conclusions in oral and/or written form, including a ***formulation*** of models for the phenomena in question and ***evaluation*** of the models by comparison with data.

- Technical terms and representational tools are introduced by the teacher as they are needed to sharpen models, facilitate modeling activities and improve the quality of discourse.

- The teacher is prepared with a definite agenda for student progress and ***guides*** student inquiry and discussion in that direction with "Socratic" questioning and remarks.

- The teacher is equipped with a ***taxonomy*** of typical student misconceptions to be addressed as students are induced to articulate, analyze and justify their personal beliefs.

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[39] Hestenes, D. (1996). "Modeling Methodology For Physics Teachers" 1996 Proceedings of the International Conference on Undergraduate Physics, College Park, p. 6.

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Clement J. (1983). *Observed methods for generating analogies in scientific problem solving.* Amherst, MA: University of Massachusetts. (ERIC Document Reproduction Service No. ED 286 746)

Clement, J. (1993), *Using bridging analogies and Anchoring Intuitions to Deal with Students' Preconceptions in Physics*, Journal of Research in Science Teaching, **30**(10), 1241-1257.

The article discusses the use of analogies to overcome student misconceptions in the area of mechanics. It includes a definition of alternate conceptions and demonstrates several "bridging analogies" that can be utilized to overcome student misconceptions.

Comprehensive Conceptual Curriculum for Physics, *List of Student Misconceptions.* Available on-line: http://phys.udallas.edu/altconcp.html

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Halloun, I. (1995). *Modeling Theory in Physics Instruction – A Draft.* Paper presented at the 1995 Annual Meeting of the National Association for Research in Science Teaching. (ERIC Document Reproduction Service No. ED 381 399)

Halloun, I. (1997*), Schematic Concepts for Schematic Models of the Real World: The Newtonian Notion of Force*, Science Education Manuscript No. 6052, Draft II, Jan. 5 1997. (submitted)

The article is an excellent reference that discusses the method for utilizing schematic modeling within the physics classroom. It includes many practical *examples and charts to demonstrate the use of the method within the mechanics curriculum.*

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Hestenes, D. (1996). *Modeling Methodology for Physics Teachers.* 1996 Proceedings of the International Conference on Undergraduate Physics, College Park, MD.

Complete discussion of the Modeling method for Physics. An excellent resource that includes practical examples of the Modeling method in use.

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