The Hestenes lectures on Modeling Instruction

Part 1: EXPERTISE IN TEACHING; SIGNIFICANCE OF FORCE CONCEPT INVENTORY

[June 23, 1997, morning talk by David Hestenes to Phase 1 workshop teachers. Transcribed by Jane Jackson in Nov. 1997 and edited by David Hestenes in Nov. 1999. No formatting is used because the lectures are posted on the modeling listserv for teachers. Square brackets are used for Jane's comments. David's comments are in parentheses.]

WHAT IS EXPERTISE IN TEACHING?

Some of you do not have high Force Concept Inventory (FCI) scores in your classes. I want to assure you that all that means is that you have something to learn about how to improve. There isn't anything intrinsically wrong, and we have evidence for this in the published result on Malcolm Wells. Back in 1985 we published the first data on the Mechanics Diagnostic Test, a precursor to the FCI. Malcolm Wells was the first person to apply this test to his high school class. His gains were low; his mean posttest score was about 45%, which we now know is typical for traditional physics instruction. But this was an epiphany for him, because he had put in tremendous effort at improving his instruction, and he was using most of the activities and general approach that you are using: photogates and computers -- yet he got these gains which weren't good. (Malcolm Wells didn't have "a natural gift" for teaching, by the way, but he worked very hard on refining his technique.) However, by the time he finished his dissertation, 3 years later, he made a BIG gain, among the highest FCI gains ever achieved! Today we have two people who have slightly higher FCI scores, but there are only a couple of people who have as good scores on BOTH the FCI and the Mechanics Baseline Test (MBT). This example shows that it is definitely possible to improve considerably.

Now, in the paper that was written with Malcolm Wells, (American Journal of Physics, July 1995), I really think you should review the points about "What does it take to become an expert?" There we refer to the work of K. Anders Ericsson, who has studied the development of expertise in a wide variety of activities, from chess-playing and concert playing to performance in many fields of endeavor. He doesn't talk specifically about teaching. But he comes up with some general features of those people who become expert. They are universal across the different domains. Let me review the main points.

The first point is that IT TAKES A LONG TIME TO BECOME EXPERT in any complex domain. In fact, the time period is about 10 years. Consider a person devoting all his time to playing chess. He may be a young prodigy or start later; there is an advantage to starting young, but it still takes 10 years before you can perform at the level of the outstanding experts. This is documented in areas where we have explicit data on performance. There is every reason to believe that it applies to teaching as well.

But 10 years isn't enough by itself. Another of Ericsson's conclusions is that experience doesn't necessarily produce improvement. So just because you have 10 years of teaching, it doesn't mean that you are any better a teacher than you were when you started out. In fact, with respect to concert playing with musical instruments, he has data that show that just performing in concerts doesn't improve your skill.

What DOES improve your skill? It is what Ericsson calls DELIBERATE PRACTICE and that is EXAMINATION OF YOUR OWN PERFORMANCE AND ASKING HOW YOU CAN IMPROVE IT, AND THEN TAKING SPECIFIC STEPS TO IMPROVE. That's what WE'RE trying to help you do in the Modeling Workshops! DELIBERATE PRACTICE over 10 years is as necessary to become an expert in teaching as in any other field.

There is a vast amount of data on what it takes to become an expert! (I refer you to Ericsson's review article.) After you take into account the factors about the quality of practice and the age at which it starts, it may surprise some people to learn that another factor -- namely TALENT -- isn't needed to account for variations in performance. Ericsson has considerable discussion of child prodigies, and whether or not they are necessarily more talented than others who are not called child prodigies. The conclusion is that it is not clear that there is any such thing as inherent natural talent, for physics, for example.

WHY ALL STUDENTS CAN UNDERSTAND PHYSICS

To put this in broader cultural perspective: if you look back 300 years or so, something less than 1 percent of the people could read or write. Being able to read and write was then regarded as almost magical power! Only a few people could do it. Now, almost everyone can read and write. Likewise, I think that there are plenty of reasons to believe that the kind of performance in understanding of physics and math that we think is important for a general understanding of what's going on in the physical world truly is ACCESSIBLE TO EVERYBODY. Let me support this view with some striking evidence.

The early data on the FCI precursor concerned traditional instruction only, and the gains were very small. Many other educational researchers had noted problems that are assessed by the FCI -- not with such a systematic test, but they noticed numerous misconceptions and they tried to devise ways of teaching to overcome them. For example, understanding Newton's third law was a target of a number of studies, and many activities were developed, to improve students' understanding; but the results were consistently disappointing. Why was it so difficult to get good results? Various rationalizations and alternative theories have been suggested; people talked about the "ingrained nature of basic student beliefs". It was suggested by the people who did careful studies but were not able to get good gains, that "It will take many years to change such beliefs." But now we have many examples, even in this group, of VAST improvements! I'm talking about improvements from an FCI score of about 30 percent up to 80 percent! That is huge! There were no such comparable improvements in the early efforts to evaluate the success of instruction at overcoming student misconceptions.

I want to impress upon you that addressing student misconceptions is difficult, but if it's done the right way we can make big changes! I don't want to give you the impression that there's only one right way to do this. There may be many effective ways, but we'd like to have at least one (and we have one!) :)

With regard to those of you whose students still have low FCI gains [group 3: those who had used few or no aspects of the modeling method consistently in the year after the first workshop]. Notice the encouraging thing: overall, group 3 got the greatest gains over last year.

There was not much change this year [compared to last year's huge gains] in group 1 teachers [those who have been using all components of modeling consistently], but that's to be expected. They also had the highest FCI post-test scores before they started this program. For example, Rex Rice was just mentioning to me that he had been at ASU in the 80's and had got some of the ideas and had been thinking about them long before the workshops. So the modeling program can't take all the credit for those gains. They were all doing things that are compatible with the modeling method; in other words, they had a "running start" on what we're trying to do in the classroom. I think that explains most of their original high gains; not necessarily any inherently better talent for teaching physics.

THE SIGNIFICANCE OF THE FORCE CONCEPT INVENTORY (FCI)

I want to spend some time talking about "Exactly what is it that enables some teachers to get better FCI scores in their students?" We want to solicit ideas on "What does it take to improve the FCI scores?"

But first, WHO CARES IF THE FCI SCORE GETS CHANGED? Does a high FCI score necessarily show that you have understanding? It is possible for a student to make the correct choices on the FCI for the wrong reasons. We have data that give us an indication of how LIKELY it is that they will give a correct answer for the wrong reason: Jim Minstrell's DIAGNOSER in mechanics (Jim is working in the CPU program; some of you may want to use his test) implies that 30% of correct answers to conceptual questions are given for the wrong reasons. So the FCI scores, if anything, are high. We assert that a high FCI score is difficult to achieve if a student doesn't have a coherent understanding of the Newtonian force concept.

What does the FCI score really tell us? Why do we use it? Why don't we use some other test? The main reason is that the FCI is focused on the fundamental concepts of Newtonian mechanics. Fundamentally, the six dimensions of the force concept. This includes kinematics. You cannot understand the force concept without understanding the concept of acceleration. There are many aspects of the force concept, and as you know, the FCI analyzes force into its six dimensions. The force concept, which is the CENTRAL CONCEPT IN NEWTONIAN PHYSICS, is a complex concept.

Our view in the modeling approach is that a coordinated understanding of the six dimensions of the Newtonian concept of force is what we are aiming for, and shooting for that is the most effective way to raise the student performance on the FCI. So far, all the data indicate that it IS the most effective way.

The FCI is a MINIMAL test of understanding. We claim that if you do NOT have an understanding of the force concept, then you can't have much understanding of anything else in Newtonian physics. The minimal test is: Can you distinguish a NEWTONIAN concept from naive alternative concepts that people develop naturally from their everyday experience, alternatives which aren't fully compatible with the Newtonian concept?

WHAT DO THE FCI SCORES MEAN?

[David showed a transparency like this.]

THREE STAGES OF CONCEPTUAL EVOLUTION
IN NEWTONIAN MECHANICS

1. Develop universal force concept.
    - Recognize AGENTS of force (active - passive)
    - Differentiated concept of motion (velocity vs acceleration - VECTORIAL)
        ~FCI scores up to 60%, the NEWTONIAN THRESHOLD.
2. Develop precise dynamical concepts. (Discriminate 1st & 2nd laws)
        ~FCI scores up to 80%, the MASTERY THRESHOLD.
3. Develop complete interaction concept. (3rd law)]

Now let me review what the FCI scores mean. 60 percent is what we call the NEWTONIAN THRESHOLD. (That's a somewhat arbitrary number; it could be set at 50 percent.) Below that 60 percent threshold, what is characteristic of student responses? Now, this is a generalization; there are variations among individual students, but by and large, students below 60 percent are NOT ABLE TO RELIABLY RECOGNIZE THE AGENTS OF FORCES. So that is a crucial understanding that you want to develop in your students; namely, to know a force when they see it; that is, to recognize the different kinds of forces and the agents that produce them.

A second characteristic is that they DON'T HAVE A WELL-DIFFERENTIATED CONCEPT OF MOTION. When the students start the course, their concept of motion is, "things move or they don't." And "things move faster or they move slower." But that doesn't discriminate between the concept of velocity and the concept of acceleration. So developing a reliable differentiation between the concepts of velocity and acceleration should be a primary objective of instruction. This isn't in the commonsense everyday framework of their understanding, because it requires a QUANTITATIVE means of discrimination; in particular, the VECTORIAL aspect of velocity and acceleration.

For students below 60 percent, this is where they typically have big troubles. So the instruction must be able to handle these difficulties. If they can't reliably identify the forces, then how can they understand mechanics problems? If they can't reliably distinguish between velocity and acceleration, then how can they understand what forces do?

The next stage is being able to discriminate reliably between the first and second of Newton's laws, and understanding those two laws. I won't belabor that, but what's typical of the students in the next stage, between 60 percent and 80 percent on the FCI, is that they tend to be IMPETUS thinkers; you recall that impetus is supposed to be a kind of force that keeps you moving.But that's wrong! According to Newton's first law, objects move uniformly in an inertial reference frame without any force. But students tend to think that force can be an intrinsic property that can make things move. The need for an agent of force is not recognized. That's the essence of the impetus thinking. And if you think like that, then you can't understand Newton's second law.

By the time the students get to 80 or 85 percent, the MASTERY THRESHOLD, they have pretty well mastered the Newtonian concepts I have just mentioned.

What is the last Newtonian insight that students develop? It's a mature balanced concept of INTERACTION, as opposed to just ACTION; Newton's third law is the key part of it. So Newton's third law is typically the last thing that students truly understand. As I mentioned before, we have a large amount of data, including data on two groups of graduate students; something like 20 percent of graduate students in physics still don't have a full understanding of Newton's third law. This is despite the fact that all graduate students can state Newton's three laws. But understanding requires much more than being able to state them. Understanding, of course, means KNOWING HOW THEY APPLY, and that has to do partially with this issue of "Is physics relevant to YOU?"

WELL, PHYSICS ISN'T RELEVANT TO STUDENTS, I THINK, UNTIL THEY GET TO THE POINT WHERE THEY CAN RECOGNIZE THAT THERE ARE FORCES ALL AROUND THEM; EVERYWHERE THERE ARE FORCES ACTING. That's the universality of force. Before they get to this universal concept, they have the idea that there are other influences on motion besides forces, and they think of forces as consequences of human action. Well, we've been through all this. And I think you realize that if they can't overcome these naive concepts, then there's little hope for them to understand the more sophisticated things that go into the course.

[A teacher asked if the instructors can really expect to see this sequence of understanding. Dave's reply was yes, in general, that this is what they found in looking at item analyses of the FCI. The teacher asked for more discussion of the process of learning Newton's third law. Dave elaborated as follows.] They'll recognize Newton's third law in some contexts and not in others. The hardest one is the third law in MOTION. You all know the FCI question about the little car pushing the big truck, which is one that graduate students often miss. Why do they miss that? Because there's something else operating: they have a metaphor of forces as like war or conflict, and they know from their experience that if there is a conflict, there is a WINNER; and the winner is usually the big guy: the big truck. But sometimes the winner is a little guy with a lot of energy. Otherwise, how could the little car be moving the big truck unless it exerts a greater force. So the intuition hasn't been fully educated, and that applies even to physics graduate students. We don't have data on physics professors.

We do have data on physics professors on the MBT, however. Even professors make mistakes on the MBT, but they can usually correct them when the mistakes are called to their attention. Of course everyone makes mistakes frequently; mistakes are unavoidable. Our objective should be to develop the capacity of students to EVALUATE what they do, so that they can RECOGNIZE mistakes and then know what they should do about CORRECTING them. It's not being RIGHT that really matters, but being CONSTRUCTIVELY CRITICAL.

(When the FCI was given to graduate students in the one study that we did, it was a better predictor of performance in graduate school than the Graduate Record Exam. The MBT was an even better predictor; this is because the FCI has a ceiling effect, but the MBT spread them out. With the MBT we got an almost perfect correlation betweeen the rank ordering in graduate mechanics and the MBT score. Why is it such a good predictor of performance in graduate mechanics? Graduate mechanics is Lagrangian mechanics, which doesn't really use the basic Newtonian concepts, so why should there be a correlation? My hunch is: What the MBT is evaluating for graduate students is not so much their understanding of basic mechanics as their ability to recognize flaws in their own reasoning, and to correct them. They've had four years to discover that they didn't get these things straight in freshman physics, and a lot of them never found this out -- never found the flaws in their own understanding. This is what the MBT measures at the higher levels, I think.)

We can identify three stages of conceptual evolution of understanding Newton's laws. (See transparency.) This classification comes from analyzing the content of the questions and the kinds of mistakes that students make. The mastery of the questions is not NECESSARILY in that order; the order may be influenced by the instruction that the students have. But from a logical point of view, you can see that there's a certain necessity for this sequence: you can't understand Newton's second law until you can reliably distinguish between velocity and acceleration.

Hestenes lectures, Part 2

HOW CAN WE DEAL WITH STUDENTS' PRECONCEPTIONS?

The question is; what do we DO about this? The highest posttest class averages are typically about 80 percent, which is quite good! In fact, it's quite good to get ANYBODY over 80 percent! With the original data, of some 700 students of 17 teachers who were not in Malcolm Wells' classes, almost no students got over 80 percent. But Malcolm Wells had half of his class of 30 over 80 percent. That's not a small effect. What did he do? And what can we do? How do we overcome these misconceptions?

[David showed a transparency like this.

HOW TO OVERCOME MISCONCEPTIONS

- Avoid a piecemeal approach.
- Conceptual change requires recognition of better alternative.
- First teach a unitary concept of force. The concept of force has six dimensions. Stress the universality and coherence of the Newtonian system.
  Elicit student alternative concepts in this context when they are prone to conflict. The instructor must anticipate student conceptual difficulties, focus student attention on crucial issues, bring discussions to a satisfying closure, repeat. This requires planning, preparation and practice.
- Concentrate on the three major misconceptions:
    1) "Force is action."
    2) "Motion implies force."
    3) "Force is war."

The first point is to avoid a piecemeal approach. Someone should try this, as an experiment: start out the course by giving the FCI and give them all the answers. Go over the test before you teach the course and say, "here's the answers to this question, etc." Give it to them again at the end of the course. Of course the reason why giving them the FCI answers doesn't work is that the distractors are so attractive. Even if they memorize the answers, it takes only a few days for them to forget.

In the early days, we would hand out the FCI to the teachers and tell them not to talk about the questions, but a couple did, and we could tell from the profile of responses to the FCI questions. The FCI profile is very similar from one class to another. Question by question, you can look at the profile, at which questions people do well at, and it's similar among classes. You can look at the overall shape of which questions students do well on, and tell which questions were talked about. If particular questions are discussed and the answers passed out by the teachers, this shows up on the FCI as a blip over a few questions: the questions that were discussed. There's a much higher score on those questions.

The first thing that doesn't work, as shown by the other research, is a piecemeal approach like, "Okay, we'll take the first question, here are the misconceptions, here are the right conceptions." That's talking about the answers and saying "this is right, and that's wrong."

What we need and what we're striving for is more than a change in the answer. We are aiming for a change in the conceptual framework of the students: how they THINK about things.

Conceptual change - if you're going to give up your view, it requires, in fact, another view that you recognize as a better alternative. Somebody just TELLING you that there's a better alternative is not sufficient. The student must come to RECOGNIZE that there's a better alternative.

So the modeling approach, instead of directly attacking the misconceptions of the students, first concentrates on teaching the unitary concept of force, with all of the six dimensions of the concept of force. Let me remind you that the six dimensions of the concept of force correspond to Newton's six laws shown on the overhead. Well, I won't go into that.

[David referred to a transparency like this.]

NEWTONIAN THEORY DEFINES THE NEWTONIAN WORLD*

ENTITIES: particles and bodies = {systems of particles}

KINEMATICAL LAWS.
Zeroth:
1. Every particle k has a definite position xk with respect to a given reference frame.
2. The motion of the particle is represented by a trajectory xk(t).

DYNAMICAL LAWS.
First: An inertial system is a reference system
in which every free particle has a constant velocity.
Second: In an inertial system, the net force equals the
mass times the second derivative of position with
respect to time: Fk = mk times [d2xk/dt2].

INTERACTION LAWS.
Third: F12 = -F21
Fourth: [superposition principle]
Fifth: F12 = F(x1 - x2, v1 - v2)

[NOTE: k's, 1's, and 2's are subscripts.]

* This transparency was taken from: "Modeling Games in the Newtonian World." D. Hestenes, Am. J. Phys. Teachers Vol. 60 No. 8, Aug. 1992.

[Ludwik Kowalski, a college teacher enrolled in the Leadership workshops, asked if teachers should show the students this transparency.]

You're going to teach them the concept of force, but not by lecturing. I think the list may be useful in summary. In fact, I think using this exact transparency would be worthwhile in helping students understand what the concept is about. We could easily talk for a couple of hours on "What do we mean by each one of these various laws?"

[A teacher said, "We can't talk about it, we have to demonstrate it."]

No, we must talk about it too. We'll talk about how to do that. We can't expect students to invent Newton's laws. What we can expect from them is to discriminate between Newton's laws and and common sense alternatives, and have good reasons for choosing one over another. That's what we want.

But this is crucial: to develop their understanding of modeling, we are taking a constructivist approach, which means that the students must construct their own knowledge, their own understanding. You cannot give it to them. However, you can give them TOOLS. THE QUALITY OF THE UNDERSTANDING DEPENDS CRUCIALLY ON THE TOOLS THAT THE STUDENTS HAVE AVAILABLE! So you must be prepared to give them the tools at the right time. Now, the typical physics textbook doesn't discriminate between the TOOLS and the things you BUILD with the tools. It just presents 'one damn thing after another!' So having something like this transparency plays a definite role, and I actually used this when I was teaching the introductory university course several years ago.

But what is its purpose? What keeps it from being a list of indiscriminate things? That we must talk about, and that brings us to the notion of modeling.

The unitary concept of force should be taught, stressing the universality of force. Remember to emphasize that force is the ONLY thing that influences motion. We want the students to "see" forces everywhere, to be able to analyze things in terms of forces and to understand the coherence of the Newtonian system. Doing that takes the whole semester! But that's what we aim at.

Now, where do misconceptions come in? As students do activities to understand Newton's laws and how they are used, the results will come into conflict with their common sense intuitions. What the teacher must do (and this requires much planning, preparation, and practice), is anticipate the conceptual difficulties that students will have in a particular domain. They must focus the students' attention on the crucial issues and bring the discussions to a satisfying closure. There must be a point! You can't have random discussions. It's not enough to have students just talking about things. They must learn to focus on a particular result!

[Jane’s summary of this: 1) anticipate conceptual difficulties of students in a particular domain, 2) focus student attention on the crucial issues, 3) bring the discussions to a satisfying closure.]

There is a long list of misconceptions identified by researchers, but our experience so far is there are THREE MAJOR MISCONCEPTIONS, which corrrespond to Newton’s three laws [Newton’s first law: “Motion implies force.” Newton’s second law: “Force is action.” Newton’s third law: “Force is war.”]. I’ll say more about that later on, and we will address those major ones quite specifically.

If you take care of those three major misconceptions, it appears that the minor ones fall away pretty much by themselves. You don’t need to address every little detail, because when the students get the coherent Newtonian system, things fit together and these other details take care of themselves.

Hestenes lectures, Part 3

SCIENTIFIC DISCOURSE: A CRUCIAL OBJECTIVE OF TEACHING.

[Jane's summary: By discourse we mean all the interchanges in the classroom, including whiteboard presentations, which are crucial devices for focusing and directing discourse. Getting the students to talk is not enough! Classroom discourse is aimed at raising the level of talk to scientific discourse. A goal is for people to be able to justify beliefs and evaluate claims in life.]

We have the modeling cycle, but some teachers using the instructional modeling cycle get better results than others. What is the difference? I believe that one of the major differences is the way that discourse occurs in the classroom. I want to solicit your opinions on this because you are all experienced practitioners.

One of our objectives should be to engage students in scientific discourse. How do you talk about things in a scientific way? The Modeling Method is aimed at systematically doing that, and identifying the crucial factors. What does that mean? An important task of all of us in our society is to formulate and evaluate scientific claims. Scientific claims can be predictions or they can be explanations. How do you formulate a scientific claim clearly? How do you evaluate it? This, of course, is something we want students to be able to do in LIFE! A general capability! to be able to evaluate people's claims in life situations. But before you can evaluate a claim, you must express it clearly! From the modeling point of view, we need MODELS for evaluating the claims. We need:

1) models, to formulate and evaluate scientific claims,
2) methods to investigate the applicability of these models,
3) data, to evaluate the models.

All of this is aimed at justifying beliefs! We want students to have responsibility for their own knowledge. That means, instead of asking the teacher, that they must be able to come up with their OWN arguments.

I think it's worthwhile talking about this explicitly with students in class. If they want to be the victims of all kinds of unfounded claims which pervade our society, then they don't need to pay attention to these things. But if they want to protect themselves from unjustified claims, to be intelligent members of the society, they need to be able to make judgments on their own: they must evaluate evidence to some degree. That includes understanding the STANDARDS of evidence. That helps you evaluate whether someone who claims he's an expert really IS an expert. [David told how his daughter ran through a glass door and it sliced her arm lengthwise, and she needed reconstructive surgery on her hand. They consulted with two neurosurgeons. One, highly recommended, spoke in generalities, so Dave became suspicious. The second neurosurgeon gave them a detailed explanation of what was wrong, what he could do, and the prospects. They could evaluate it -- check it out; and the foundations were that the problem was EXPRESSED

CLEARLY and CONTAINED DETAILS. So a key to evaluating claims of so-called experts is to see what kind of details they come up with in their analysis.]

We know that there are differences in the way the discourse is handled in the classroom. I am setting up now an objective of improving the scientific discourse. That's a primary objective of our program. This raises questions about managing classroom activities and discourse, the subject of my next overhead.

[John Hollis, a teacher in the Leadership Modeling Workshops, pointed out that teachers have different ways of handling silence. A teacher asks, "Any questions?" Silence - and one teacher will go on, assuming that everyone understands. But another teacher will not be satisfied with silence and will ask further probing questions, to ferret out further misconceptions or to evaluate whether students really understand.]

[David Hestenes said in response:] What I want to promote is much richer discourse, not just direct interchange between teacher and student. The discourse will go on in different modes at different times, so there are different objectives. One is to improve the quality of interchange among students. We want the students to use terms correctly; to present coherent arguments. We know that in some of your classrooms students stand up and give wonderfully coherent accounts on their whiteboards. So the discourse includes the presentations of the students; not just questions and answers by the teacher; that's only one mode of discourse. The overall quality in the way things are talked about is our main concern. What we want to see in the classroom is a general improvement at that level, however it's achieved.

[John Hollis spoke on the importance of establishing a classroom attitude of respect for various viewpoints, rather than put-downs by teacher or other students. "If the attitude is promoted that the discourse is a healthy thing, and everyone is respected, and that they're expected to do this, then there's going to be much more success."]

[David Hestenes said in response:] You're exactly right; in fact, the FIRST thing the teacher must do is to establish a climate of openness, one where students feel free to make mistakes; where it's IMPORTANT to make mistakes, in fact! This is particularly developed in the discussion of the modeling cycle [in the American Journal of Physics paper entitled "A Modeling Method for high school physics", July 1995] as I reviewed the way Malcolm Wells did it. In opening the discussion to understand what's going on, Malcolm engages the entire class. He doesn't make an evaluation of whether the student has it right or wrong but tries to engage the students in doing the evaluation themselves, insofar as they have the tools to do that!

When there are crucial tools that can simplify or clarify the matter at hand, such as, early on, to discriminate between dependent variables and independent variables, that concept must be presented by the teacher. So the teacher must know how to make sharp and reliable definitions, not just vague definitions. There are many, many details that go into this. In fact, the whole understanding of physics is reflected in the discourse!

The concept of discourse includes all interchanges or communication in the class -- among teacher and students and among students. It includes the whiteboards themselves; in fact whiteboards are powerful devices for generating and controlling discourse. So the quality of the discourse will be reflected in the quality of representations that appear on the whiteboards. That's why establishing standards for what goes on the whiteboards is important. That has to do with the crucial role of MODELING in understanding.

So the first point about managing classroom discourse is that getting the students to talk isn't enough. Without the guidance of the teacher they will just ramble. The teacher must find means to control the discourse. There are all kinds of ways. There is no need to follow the modeling cycle slavishly. The modeling cycle was designed to incorporate all the features of modeling into it. But there are many variations of the modeling cycle. The crucial thing is TO RAISE THE LEVEL OF DISCOURSE: namely, how the students formulate and evaluate claims. A key to doing that is recognizing that formulating and supporting claims involves creating and evaluating MODELS.

HOW DO YOU MANAGE CLASSROOM DISCOURSE?

(1) The teacher starts by setting a classroom climate [of openness, where students feel free to make mistakes] and establishing the subject of discourse. This is often done by demonstrating a phenomenon and posing a problem. The teacher is responsible for leading the discourse so that issues and questions are raised and claims can be made that are WORTHY of investigation. This doesn't need to be something that students go into the lab to do; the investigation could be something that you go on the Internet to find out information about.

(2) Here's a crucial point. Communication requires shared meaning. That means, when you use the word "force", the student must ascribe the same meaning to the word as you do. Results of the Force Concept Inventory say that this is not happening in traditional instruction. The teacher is rambling on about forces and the students have a totally different idea of what those words mean. Consequently, the students are systematically misunderstanding.

How do you get to a common understanding? You get students to use the term to find out what it means to them. You don't condemn their usage, but you say, "Do you really mean this? or do you mean that?" You are adjusting the students' conceptual framework to the external frame. So a big initial part is setting up a framework in which everyone has a common understanding of the use of terms. As the students master the basic vocabulary, the basic ideas, things get better!

(3) Of course, scientific discourse is not just a matter of vocabulary; it also involves models, which are conceptual structures. The meaning of words, equations, and diagrams is constructed from situated use! This is a big emphasis in current research, not only in science education but also in linguistics and other fields. How is a common meaning of words constructed? From SITUATED USE: you see how so and so uses that term in a SITUATION. And these meanings must be negotiated.

(4) The quality of the discourse depends on (and this is a crucial point, where the Modeling Method differs very significantly from other approaches!):

- the representational TOOLS at the students' disposal, and how they are used,
- the structure of the arguments, and
- the standards of the argumentation (which are set by the teacher). We haven't said exactly what these standards are. This is a worthwhile job for one of our action research teams.

There is strong reason to believe that high quality scientific argumentation arises spontaneously among the students when they have the DISCURSIVE RESOURCES: when they have learned the right terms, when they have a suitable situation (created by the teacher).

Getting together a whiteboard action research team is important. There's been lots of talk among teachers about the appropriate place for whiteboards. Teachers use them in different ways. We could profit by setting up criteria for their use. There are issues about time management, pace, wait time, students' preparation, their role in criteria for grading, objectives, results. But the most important thing about the whiteboard is that the WHITEBOARD EXTERNALIZES OUR CONCEPTUAL REPRESENTATIONS.

We need conceptual representations. A good whiteboard is something that people can SEE. We know that there are verbal representations, but I do not think that a verbal representation should BE on the whiteboard. There shouldn't be long sentences describing what you did. A few key TERMS should be there, an appropriate GRAPH, maybe even some illustration of the experimental apparatus. A DIAGRAM of some kind -- it could be a single free-body diagram. You need to think critically about the representations. The whiteboard then forms a focus for discussion; and the students' understanding of what's up on the whiteboard can be explored by asking questions. That's all part of negotiating meaning: the meaning and understanding of these external representational tools. These representational tools are primarily diagrams, graphs and equations of particular kinds. The role played by WORDS is mainly DISCUSSING these external representational things. Words are difficult to survey when they are written down.

THE ROLE OF TEXTBOOKS

[Ludwik Kowalski noted that the teachers in the group have many different attitudes about the role of a textbook. Some ignore them, saying that they interfere with what they are doing. Others say that textbooks are important references. He asked David Hestenes for his view of the role of the textbook in the modeling method.]

The evaluation of any textbook or tool must be based on the question, "How does it contribute to the overall objectives?" I know of only one example of effective use of a textbook in instruction, and that is by Eric Mazur at Harvard. Mazur has the students read the textbook but he doesn't go over the material in the text. When the students come in each day, they must answer a question about what they have read, to see if they have read the material. The question doesn't require deep understanding. In his case, the textbook is a major source of knowledge. He assumes that the students can read the textbook, and by and large Harvard students can read textbooks. But not as well as you might wish, for the reading of a science textbook requires special skills. Most students don't realize that to be an effective reader you must read with a question in mind; they must be asking: "What do I want to get out of this?" You don't just read one thing after another. I like the definition of a book by the philosopher and literary critic, I. A. Richards. His definition of a textbook is "a machine to think with." The textbook has coded information, and you must learn how to get the information out. I have learned most of my physics from reading scientific books and papers, but this is a skill that takes a long time to develop; so we should be helping our students to develop skills in reading. It is a non-trivial matter!

Unfortunately, textbooks are not written in a way that's conducive to learning. You have to understand the material in order to get what's in there; that's why a physicist or physics teacher doesn't have much trouble reading the books. But the student is unable to discriminate between basic models and peripheral information. The models that we're considering are not unique to our program; they are inherent in all textbooks. But the models are BURIED in the textbooks. To understand the textbook requires being able to RECOGNIZE THE MODELS. This is acquired by long experience by physicists and physics teachers, who develop these models implicitly, without being aware that they are doing so. There's plenty of evidence that they have these models and use them. A good example of the evidence is if you give physicists a projectile motion problem. They don't read the whole problem before they do it. They read one sentence and say, "Oh, that's a projectile problem." Then they start drawing a diagram and solve the problem. They are SELECTING A MODEL at the beginning, and that's what the students need to do; to ask, "Is there a model here? and if not, do I need to make one?" THE MODEL IS THE OVERALL STRUCTURE - WHICH THE STUDENTS DON'T SEE IN TRADITIONAL INSTRUCTION. Our objective is to make the models explicit and transparent for the students. So I encourage people, if they have effective ways of using a textbook, to tell us. But because of the way the textbooks are written, many teachers find they are not helpful, especially in high school classes.
[The group broke for lunch.]

KATHY MALONE spoke on her IMPROVEMENTS IN METHODS of discourse and reflection

(1) Tests. After a test is graded and given back, students must look at their mistakes, write down what they were thinking - explain their error, and find the right answer, and turn in the test again in order to get a grade for the test. (Allison Lide did this, too.) Easy to do, doesn't take much time.

(2) Reflective journal. Kathy reads them, and then students must answer Kathy's questions completely and turn them in again, before she accepts their grade. Took much time.

(3) She notes which test questions are commonly missed, and then gives similar questions on the next test. Thus she can SEE the improvement in understanding.

(4) She has students tell which questions are associated with which of Newton's laws.

[Later, Kathy wrote 2 pages of decription of these activities; available upon request from jane.jackson@asu.edu]

Other teachers contributed good ideas to the discussion on discourse, too.

Dave Hestenes noted that we want students to learn to evaluate themselves. He suggested that EXEMPLARY WHITEBOARDS BE PUT ON THE CHALKBOARD, AND THAT EXEMPLARY LAB REPORTS BE HANDED OUT TO THE STUDENTS.

Hestenes lectures, Part 4. Afternoon session:

COGNITIVE FOUNDATIONS FOR THE MODELING METHOD.

I want to talk about the cognitive foundations for the Modeling Method. Physics teachers and physicists talk a lot about physical intuition and physical insight. But what does it mean to understand physics? What do we mean by physical intuition? and physical insight? I would like to address these questions from the point of view of our modeling theory.

Fundamentally, what we do in physics is an extension of what people do all the time. They try to make sense of their experience. One view prevalent in the cognitive research literature is that people make sense of their experience by constructing MENTAL MODELS of how the world is working. What are they going to do tomorrow, or the next day, or whatever? Their plans are cast in the form of mental models. What we do in science is an extension of what we do every day; and that is, we recognize PATTERNS in our experience, and then we capture or hold them by creating REPRESENTATIONS.

[Jane's note: In sum, to make sense of experience is to recognize patterns and to hold them by creating representations of our experience.]

We use these basic tools to make these representations:
(1) metaphors
(2) analogies
(3) models.

The skill with which people use metaphors, analogies, and models, I will argue, is a major component of their INTUITION and their INSIGHT. We use PHYSICAL INTUITION to represent structure in physical systems and processes. And to have PHYSICAL INSIGHT is to be able to RECOGNIZE such structure.

I've already noted, and will say more about this, that students use metaphorical thinking in their analysis of questions on the FCI. Many researchers in cognitive science, led by George Lakoff, argue that metaphors are a fundamental component of human thinking. We use metaphors in everyday thought and speech much more than we are aware of. [Jane's note: See the book entitled METAPHORS WE LIVE BY, by George Lakoff and Mark Johnson, U of Chicago Press, 1980.]

What is a metaphor? We'll get into that. But let me first say that we don't want to discourage students' use of metaphors. Rather, we should aim to TAME their metaphors. We must guide students to reconstruct their metaphors in ways that match the physical intuition that we want them to develop. And our intuition is fundamentally grounded in the way we use metaphors having to do with our bodily experience in the physical world.

An ANALOGY is a more explicit formulation of the relations in a metaphor.

Finally, for scientific purposes, we use the following explicit definition of a model: a MODEL is a representation of structure in a real system or process.

[David showed a transparency like this.]

pattern <---------------- analogy -----------------> model

PHYSICAL WORLD   NEWTONIAN WORLD
                              representation
physical phenomena -------------> models of physical phenomena

                              interpretation
                              <--------------

The ability to recognize and represent patterns by the use of metaphors, analogies, and models is the ability to develop intuition and insight. There are particular ways to do this for understanding physics. That’s the theme that I want to develop.

[David showed a transparency like this.]

MAJOR BELIEFS ABOUT FORCES

NEWTONIAN CONCEPTS vs NAIVE BELIEFS   RESULTS

1st law vs “Motion requires force” (impetus principle) (~60%)
2nd law vs “Force is action” (no passive forces)   (~40%)
3rd law vs “Force is war” (dominance principle)   (~90%)

Let’s talk first about the three major naive beliefs about forces. These RESULTS (on the transparency above), by the way, relate to posttest FCI scores of the students who still hold these erroneous beliefs after they have completed calculus-based physics. These are the percentage of students who are still using these metaphors, such as “force is war” instead of Newton’s third law in their physical reasoning; their concept of interaction doesn’t fit the scientific conception.

Now, it’s very important to have an intuition about interacting forces that is associated with your own action [because that provides bodily experience for thinking about it.] That is a role for metaphor!

By the way, there is an extensive study of these matters by Andy DiSessa (of Berkeley) that’s almost the length of a book. He doesn’t mention the word ‘metaphor’; he calls the units of physical intuition P-PRIMS, or physical primitives. Essentially, the idea is that from our experience we develop a set of familiar patterns. In particular, we have a sense of spacial relations; and we use our understanding of space to structure our understanding of other things. For example, we use our spatial intuition whenever we are ORDERING or RANKING. Up is good, down is bad; up is more, down is less, right? The stock market goes up; the stock market goes down . . . Those are geometrical examples of metaphors; and those metaphors are grounded, truly deep-seated, in our bodily experience in this world. We use the structure of our bodily experience to provide structure to new situations; this is the fundamental use of metaphor.

Notice that it uses structure. A metaphor uses structure in one domain with which we are very familiar, to lend structure to a new domain with which we’re not so familiar. In my view, the difference between a metaphor and an analogy is that an analogy does this more explicitly, whereas the structure in a metaphor is more implicit. Such is the case for the three major metaphors about forces [on the transparency above]. I leave it to you to elaborate the structure of these metaphors.

[David showed a transparency like this.]

PHYSICAL ANALOGIES (Camp & Clement, 1994)

anchor (or source) -------> bridges -------- > target
| ↓ |↓
model property same property

[Please interpret the vertical lines as arrows pointing downward.]

A metaphor has a SOURCE in some domain with which you’re very familiar. And it has a TARGET in another domain with which you’re NOT so familiar. By comparing the source to the target, you structure the target domain. So a metaphor is a mapping of structure from one domain to another.

P-prims are perceptual and behavioral units, source elements with coordinated structure. In the work of Piaget, they are called schemata. Out of these things we build our physical intuition. Our understanding of force does require that we use the notion of force as a push or a pull, because that relates it to our direct experience [e.g., gives us a sense of mechanism]. An intuition of push or pull then becomes a p-prim for universal force. However, if the metaphor is set up incorrectly, then it generates misconceptions about force that we mentioned earlier [e.g., the dominance principle]. That is a misuse of metaphor.

[Joseph Vanderway, a Phase 1 teacher, asked, "Is that the predominant definition of force, that it's a push or a pull? Because in my course, I emphasize strongly that a force is an interaction between two objects or systems that RESULTS in a push or a pull."]

No, because that's not a definition of a force. The definition of a concept specifies how it's related to other concepts within a conceptual system. What we're talking about here is how you articulate the concepts with your own intuitive experience. That's the function of metaphor, I'm saying. 'A force is a push or a pull' is not a definition; it's a mapping of a concept of force onto our bodily experience of space. It's an old metaphor that's often used by physics teachers. The problem is that students think of the "push-or-pull" metaphor differently than teachers, and then they elaborate it into misconceptions.

What we want to do is re-educate the way people use their metaphors, as part of developing their intuition. That's all I'm suggesting.

The physical intuition of a force as a push or pull helps the students develop A SENSE OF MECHANISM that underlies the concept of force. We want to make that mechanism personalized in their own experience. The wrong intuition is the misconception that "force is action" from which you can infer (wrongly): "force requires action; therefore tables don't act because they're inert." We want to help students develop their intuition into a universal concept of force.

How can we do that? That's one reason I've invited John Clement to talk to you tomorrow, because he will give you an explicit discussion of how to educate the intuition in the systematic way by the use of analogies [his bridging analogies]. You have your workbook [Camp and Clement: PRECONCEPTIONS IN MECHANICS]; look at it. He doesn't describe it in the same way that I do. One of my objectives is to prepare you to use his material, which I think will be very valuable. I want to give you a framework for fitting it into the modeling approach.

The way we use metaphors to relate physics concepts to our personal experience is a way of developing physical intuition.

Analogies relate structure in one part of experience to another part of experience. The parts are the same in some ways and different in other ways. It's the sameness that interests us.

[David showed a transparency like this.]

THREE TYPES OF ANALOGIES

1st physical system <---------> 2nd physical system
physical
| ↓ | ↓
↓   ↓
first model   <----------------------> second model
formal analogy

[Please interpret the vertical lines as arrows pointing downward.]

There are three distinct ways that we use analogies in physics. I want to encourage you to use exploration and formulation of analogies a LOT in your classes. It will be valuable to get students to draw analogies and find their limitations.

[Analogy type 1: Two physical systems] First (and Clement will talk about this), we have ANALOGIES BETWEEN DIFFERENT PHYSICAL SYSTEMS. The systems are the same in some respects. Now in developing a universal concept of force, we look at interactions in different physical systems in different places and we ask, ‘How are they the same?’ We go then from a specific to a general concept where we see them all as analogous: as many instances of one phenomenon which we call force.

I’m talking about an analogy between two physical situations. You identify one physical system or situation as being like another; that’s an analogy. In fact, when we use a model in diverse situations, we are actually using an analogy; we are saying that the structure described by the model is the SAME in these different situations.

[Analogy type 2: Physical system and a model] This leads us to a second kind of analogy. The definition of “model” that we use is that a model is a representation of structure in a system or a process (and a process always involves a system anyway: a system or its behavior.) So here we have A MAPPING OF THE STRUCTURE IN THE PHYSICAL WORLD ONTO STRUCTURE THAT WE WRITE DOWN AS EQUATIONS OR DIAGRAMS, ETC. We have formed an analogy between these two very different things. For example, when you use MBL probes, and you look at a graph and you correspond that to a motion, the idea is to see the graph as a model, a representation of structure in that motion. Then you must ask, ‘What is the same about them?’ The things don’t look the same at all, but they have a structural similarity. So a model, in its relation to the thing that it models, is ALWAYS in an ANALOGY.

[Analogy type 3: Formal: two models]   A third kind of analogy is within the theoretical domain.   We can DRAW ANALOGIES BETWEEN A MODEL IN ONE THEORETICAL DOMAIN AND IN ANOTHER. That is called a formal analogy. For example, in the CASTLE project, you use electromechanical analogs -- quite a number of these -- such as an analogy between pressure and voltage.

Within a single theory, different models are related by common theoretical principles or laws [such as conservation of momentum or energy. For example, if we have two models, both satisfying momentum conservation, they are analogous. Momentum conservation specifies a structural pattern in each of the models.] This is the strongest kind of analogy: analogous structure regarded as common structure. In mathematical terms, the analogy becomes an isomorphism.

To summarize: The range, the validity, and the theoretical content of a model are determined by three kinds of analogies:

(1) The SCOPE OF A MODEL [physical analogies: first physical system is analogous to second physical system]. When we have a model and it applies to a certain range of things, all the different things that it applies to are analogous, in that they all have the same STRUCTURE. So when we talk about a model that applies to many situations, what we're doing is using the model to represent a common pattern or structure. This model captures the common structure in all these different situations.

(2) EVALUATING THE MODEL. [Matching a physical system to the model you are using for it: i.e., in the transparency, matching the first physical system with the first model, listed under it.] When you are validating a model, for example, one that you're using to interpret an experiment, you are evaluating the degree to which the analogy holds, i.e., the degree to which the structure of the system is represented in the model.

(3) Theoretical principles to RELATE MODELS of different kinds (first model is analogous to second model).

THE COGNITIVE PROCESSES THAT WE USE TO UNDERSTAND SCIENCE INVOLVE CONSTRUCTING MODELS AND COMPARING STRUCTURES.

[Ludwik Kowalski asked Dave to say more about the types of analogies.]

WE draw the analogy [i.e., it's not automatically there in nature]. The analogy is recognition or identification of a similar pattern. The analogies we are drawing are between physical things versus conceptual things. We have two worlds here to work on: an invented world, which is our Newtonian conceptual world in which we construct models, and a physical world of real objects and processes. In this physical world, we recognize PATTERNS. We have a pattern in two different places. It's a [physical] analogy to see the patterns in two different places. These are two different [physical] systems; we draw an analogy and see that they are similar.

[A teacher said: "For example, in CASTLE we make an analogy between an electric circuit and a fluid circuit. They are both real circuits."]

The analogies aren't out there in nature; they are waiting for us to draw them. If we can draw them, those structures must be implicit in nature or the analogies would not hold.

An analogy is a mapping of one structure onto another structure. It’s a similarity of structures. If two things are analogous, it means that they are the same in some ways and different in other ways. We’re primarily interested in SAMENESS of structure.

There are good analogies and bad analogies; useful ones and useless ones.

[Analogy type 3 again: Formal analogy] [He discussed a transparency showing the differential equations and system schema for a mechanical damped forced oscillator and for an LRC circuit.] Later we can teach our students to draw an analogy between MODELS. One powerful example is this electro-mechanical analogy. This is an abstract model. Physicists often talk about a mathematical model, and this is a favorite one: the damped, forced harmonic oscillator. The differential equations are for an LRC circuit and a mechanical damped, forced harmonic oscillator. This is an electro-mechanical analogy: the models are identical in the form of the equations. This is a 100-year-old analogy, used a lot; but one important point has usually been missed in discussing it: not everything about the models is in the structure of the differential equations. An important difference is that there’s no concept of a “complete circuit” in the mechanical case. The system schema of both systems SHOW the crucial difference between the electric and the mechanical analogies. Thus, the models are the same in some ways but different in other ways. THE FAILURE TO RECOGNIZE THAT THE STRUCTURE OF THE MODEL IS DISTRIBUTED ACROSS SEVERAL REPRESENTATIONS ACCOUNTS FOR SOME OF THE PROBLEMS THAT PEOPLE HAVE IN UNDERSTANDING PHYSICS.

Hestenes lectures, Part 5. Summer 1997 at ASU to 50 teachers in their 3rd Modeling Workshop

WHAT DO WE TEACH?

The question "What do we teach?" has to do with "What do we want to learn?" A common instructional objective now is "We want students to think like a physicist." This raised a question by the most famous physicist of all, Albert Einstein, who asked, "What, precisely, is (scientific) thinking?" We have a working answer to Einstein's question. Our working point of view is: MODELING, that is, MAKING AND USING MODELS IS SCIENTIFIC THINKING. Therefore, if you want to develop skill at scientific thinking, you develop skill in making and using scientific models.

One point that I want to emphasize over and over again is that powerful thinking requires powerful modeling tools, which are primarily representational tools! People talk about mental models and concepts as if they are entirely in people's HEADS. I do not buy that! Because when people are thinking about physics, there's an interaction between what they're thinking in their head and the external representations (diagrams, equations, etc.) ALL of that is involved in our understanding.

Now, mental models are INTERNAL representations of structure; this is the way that I'll use the term. I see a lot of use of the term "mental model" without specifying clearly what it is supposed to mean. A model, as a representation of structure, must have the structure embodied somewhere in some concrete system. For example, you can make a model of the geometric structure of an airplane by building a little model airplane, and then the structure is embodied in concrete material (and is not a mental model but rather is a concrete model, which is an EXTERNAL representation of the airplane's structure). But a MENTAL MODEL is embodied within the structures in the brain.

Now, crucial but frequently overlooked fact about most of our external representations, such as a graph, is: the structure is not all in that graph, because you need to know how to READ it. So part of the structure is in the graph and part is in your head, that being the part that recognizes what is the structure that is represented in the graph. That's why students must learn how to READ graphs. That's why we must help them think of the graph as a modeling tool for representing structure. Nevertheless, much of the structure is in your head, because only YOU know what these lines mean; what the slope and intercept mean, etc.

Thus a major part of modeling is learning to use such tools so that when we all look at the same graph or diagram, we come up with the same mental images or at least ANALOGOUS mental images. I don't know what's going on in your head any more than you know what's going on in my head. But the way that we come to believe that we are thinking about the same thing is that WE AGREE ON THE WAY WE USE EXTERNAL REPRESENTATIONS. That's the way we come to shared knowledge, by agreeing on the way we use external representations, including words but especially using diagrams.

CONCRETE models, then, are EXTERNAL representations; versus MENTAL models which are embodied in the stuff in the brain. THE CRUCIAL THING IS INVENTING MEANING.

[Jane's "aha" at this point: We "know" real objects & processes by constructing models to represent them in our minds. In other words, we construct mental models, naturally and all the time. The modeling cycle is a coordinated sequence of activities that induces cognitive processes for matching conceptual models with real objects and processes. Since we are making models all our lives, if we want to think scientifically, the modeling cycle is thus fundamental to instructional design!]

I don't want to belabor the point, but I believe that the representations of models in computers is going to have an enormous educational impact in our lifetime. The reason is that when you put a diagram or an equation in the computer, you can include the structure needed to interpret it. If you have an equation, you can put into the computer the syntax [the rules of algebra that make it a well-formed equation] of the equation; whereas otherwise you must have the syntax in your head and use it to interpret the printed page. So computer modeling tools will externalize our modeling tools even more than printing. I'm working on a project called the Modeling Workstation, to design a MACHINE TO THINK WITH. [The computer is a more powerful machine than a book.] It will have manipulative diagrams that will externalize the structures as completely as possible.

[David showed a transparency like this.]

BASIC PARTICLE MODELS IN NEWTONIAN MECHANICS.

motion <---------> patterns <----------> force

KINEMATICAL MODELS	CAUSAL MODELS
- constant velocity	free particle (net force = 0)
- constant acceleration	constant force (net force = constant)
- simple harmonic oscillator	linear binding force (net force = -k r)
- uniform circular motion	central force
- collision	impulsive force

Let me remind you that we have identified five basic particle models in our mechanics curriculum. Our model-centered instructional objectives are centered at this issue: WE MAKE SENSE OF THE WORLD BY RECOGNIZING PATTERNS AND REPRESENTING THEM AS STRUCTURES. MODELS ARE THOSE STRUCTURES. So we want to engage students in constructing and using these scientific models to describe, explain, predict and control.

The quality of the models depends on the TOOLS that are available to them: mathematical tools and diagrammatic tools. WE MUST PROVIDE THE STUDENTS WITH THE TOOLS. If we want the students to do writing, we don't ask them to invent pencils. We give them pencils. A pencil is a tool that facilitates the writing process. Likewise, we give them computer tools that facilitate the construction and use of models. We give them conceptual tools to be used in diverse ways. But we need to help them distinguish between the TOOLS and the things that they BUILD with these tools. The things that they build are MODELS. As someone once said, “Science is the name, modeling is the game.” (You’ve heard that someplace!)

Now, it happens that there is a small number of basic patterns that students must learn, to understand Newtonian mechanics. To develop insight into that structure, that content core, we have organized the course around a small number of models. [They are listed on the transparency above.] If the students just learn how to recognize, to grasp the structure of that small number of models and use them in diverse ways, then they will have learned a lot more than you learn in traditional physics instruction. So although that list looks small, it’s actually bigger than it looks. We’ll talk about it when we elaborate the models.

What do these models do? First of all, we have kinematical models on one side of the transparency: they capture particular patterns of motion that are familiar in the real world. To identify these motions, students should be able to recognize an ovoid curve (it’s got a hump on it) and know that it looks pretty much like a parabola and not like an arc of a circle. This is recognizing one gross feature of a pattern. (In this connection, I’m greatly annoyed when I look in textbooks and see a sine curve that is made out of arcs of circles -- up and down.) In part, physical intuition comes with the ability to recognize structure in perceptual experience.

So there are patterns in MOTIONS, but there are also patterns in FORCES.In fact, the investigation of the specific force laws has been the major enterprise of Newtonian mechanics for the last 250 years. That investigation is pretty much complete by now. When we analyze interactions, we find certain basic patterns among the forces that we investigate, and we incorporate these patterns into the theoretical framework for Newtonian mechanics.

I mention PROJECTILE models here, to ask, “Do we really want to think of projectiles as MODELS?” That amounts to classification of models by SITUATIONS. The term “projectile” suggests a situation type rather than a model type. Projectile models would then be situation-specific models.

On the other hand, the underlying abstract model is a PARTICLE WITH CONSTANT ACCELERATION, and a projectile is just one class of things to which the model applies. As you know, the same model applies to a block sliding along an inclined plane. Both situations are described by the same constant acceleration model.

So one of the important objectives in teaching modeling is to extract the models from situation-specific applications, so that the students can learn how to see these patterns in many different situations. Then they have powerful conceptual tools for ordering their experience in a huge domain.

By the way, this and several other overheads (transparencies) are in the paper on MODELING METHODOLOGY FOR PHYSICS TEACHERS (1997, downloadable from our web page: http://modeling.asu.edu/modeling-HS.html), which you all should read.

[David showed a transparency like this.]

MODEL SPECIFICATION

A MODEL is a representation of structure in a physical system and/or its properties. It describes (or specifies) four types of structure, each with internal and external components:

(1) SYSTEMIC STRUCTURE specifies
- composition (internal parts of the system)
- environment (external agents linked to the system)
- connections (external and internal causal links)

(2) GEOMETRIC STRUCTURE specifies
- position with respect to a reference frame (external geometry)
- configuration (geometric relations among the parts)

(3) TEMPORAL STRUCTURE specifies change in state variables
(representing system properties)
- descriptive models represent change by explicit functions of time
- causal models specify change with differential equations by interaction laws

(4) INTERACTION STRUCTURE specifies
- interaction laws expressing interactions among
links, usually as function of state variables

Gregg Swackhamer asked, when he was first learning the modeling method, “What, precisely, is a model?” The most succinct definition, one I have used over and over again and will continue to use, is this: A scientific (or physical) model is a representation of structure in a physical system and/or its properties. Therefore the model stands in relation to the system. The relationship is one of ANALOGY: model and system have a similar structure. We have a line on a graph that corresponds to a path of a moving object, for example, a line that corresponds to a velocity in subtle ways. But what KIND of structure is represented? What do we mean by structure?

From an analysis of models employed throughout science, I conclude that the various kinds of structure represented in scientific models can be classified into four types:

(1) SYSTEMIC STRUCTURE

In a physical situation we can identify a set of one or more objects that we call a SYSTEM. To make sense of a physical situation is to IDENTIFY A SYSTEM and create a representation to designate it. The representation requires us to know: what is the system? This amounts to knowing what we’re talking about. Well, a system is made out of parts, so you must specify its COMPOSITION. Now, systems aren’t usually given to you; YOU are the one who must decide which system you're going to talk about. And a judicious choice of system is often crucial to being able to recognize a PATTERN within nature. Physics, as a scientific theory, helps us make these decisions and identify appropriate ways to structure our experience. And modeling TOOLS enable us to represent the structure. To represent systemic structure a diagrammatic tool called a SYSTEM SCHEMA has been developed. An electrical circuit diagram is an example of a system schema. (See "Modeling Methodology for Physics Teachers" for more discussion.)

Part of identifying a system is recognizing how it's linked to its environment. So we must identify the EXTERNAL AGENTS linked to the system. Identifying which things are linked to which leads to a specification of the system's CONNECTIVITY.

So identifying COMPOSITION and CONNECTIVITY is the first stage in identifying systemic structure. At that stage, you don't specify what the interactions are --just that there exist interactions or other kinds of connections. The system schema is a tool for representing the composition and connectivity of a system.

(2) GEOMETRIC STRUCTURE

According to the zeroth law of physics, EVERY system that exists in this world has a geometric structure. It has an external geometric structure which relates it to the external world. We usually represent that as position with respect to a reference frame. The POSITION variable that occurs in physics is representing that kind of geometric structure. That representation of geometric structure presupposes the theoretical view that the universe is modeled as a three-dimensional Euclidean space.

There's a lot of THEORY involved in that, including a theory of reference frames. It's all part of what I call the ZEROTH LAW of Newtonian physics. Indeed, the zeroth law of Newtonian physics is a zeroth law for all of SCIENCE, because it has to do with assumptions about space and time underlying all of science: adopting a specific model of space and time. Our standard [geometric] model of the physical universe is a three-dimensional Euclidean space. When you go to a different theory, for example, if instead of playing the Newtonian game you play the relativity game, then you represent the world as four-dimensional spacetime; it's a different way of attributing geometric structure of the real world.

In addition to position with respect to an external reference frame, a system may have an internal CONFIGURATION. If a system is modeled as something more than a point particle, then you can model the geometric relation among its component parts. That is what we mean by the configuration of the system. In Newtonian mechanics, we model everything as a particle or a system of particles. (There are extensions of Newtonian mechanics to continuous systems, but that's usually done sloppily in textbooks if at all. Mostly they are modeling things as point particles without ever SAYING that they are modeling point particles.)

Geometric structure is essential to any complete model of a physical system. However, we do make models that don't include any geometric structure. For example, we often model electrical circuits by representing its systemic structure by a circuit diagram without necessarily mentioning its size, shape, or position. We're not concerned about where this electrical circuit is in space.

So you don't need to have every kind of structure represented in a model. But every model has at least one kind of structure, and if it's a COMPLETE model, it has some representation of every kind. Indeed, an electrical circuit DOES have geometric structure; and as soon as you talk about electromagnetic waves and the connection of the electrical circuit to the fields around it, you must start talking about the geometric structure; it makes a difference. But in one domain of electrical circuit theory we completely ignore geometric structure, considering only models with more limited structure, namely connectivity in circuits and flows through the circuits.

(3) TEMPORAL STRUCTURE

Temporal structure of a system is the structure of its behavior in TIME. A model of temporal structure specifies how the state variables of a system change with respect to time. There are two different kinds of models: descriptive and causal. For example, if I give the trajectory of a particle, that's a descriptive model of the motion. On the other hand, if I give the equation of motion, that is a causal model. Say a particle has a constant force exerted on it; with initial conditions you can integrate the equation of motion to get a trajectory. We can regard that as generating a descriptive model from a causal model. The causal model represents the structure of the trajectory by giving us a rule for generating the whole trajectory from a little part; that's what velocity, acceleration, and differential equations enable us to do. [Generally 'big things from little things.'] That tells you why a parabola has the particular SHAPE that it does. That shape is a feature of its overall temporal structure.

(4) INTERACTION STRUCTURE

Finally, the interaction structure, the fourth kind of structure, describes the interactions of the system [in a system schema, we represent interactions by links -- see below]. In mechanics we think of interactions as being forces of one thing on another. But there are many kinds of interactions; they don't need to be forces. In mechanics the interactions might involve energy or mass exchange as well as forces. In electric circuits the interaction is typically a charge flow between circuit elements [we think of links as wires connecting one to another so that charges flow between them.] Similarly, in economic or social systems the interaction may represent an interchange of information, or an interchange of goods, and so on.

From my scientific experience, I can't think of any other kind of structure that can't fit into one of the four categories that we have just discussed.

So when you learn to model in physics, you will learn a LOT about modeling in other branches of science. In fact, the modeling in social sciences and economics has a long tradition of trying to emulate the modeling that was done in Newtonian physics. Even so, it was a long time before people learned to do this at an abstract MODELING level, without reference to specific concepts in physics.

So modeling applies not just to physics but to every science. Thus by teaching students how to model in specific situations, we're aiming to develop general skills which are TRANSFERABLE to other situations. You can facilitate the transferability by having them draw analogies between structures of different systems. How are these structures the same? How different? If they are the same in all the respects that interest you, then you can use one model to describe them all.

[Dave talked at length about these four types of structure by using the modified Atwood machine as an example. He referred often to a transparency showing various representations of structure in a model for the modified Atwood machine. I can't draw that here. Please study it. It is Box 5 on page 10 of David's article entitled MODELING METHODOLOGY FOR PHYSICS TEACHERS. Download it from our web page. http://modeling.asu.edu/modeling-HS.html

David focused on system schema in discussing the Atwood machine example. A SYSTEM SCHEMA represents the components of a system and the links between them. The links represent interactions. The teachers asked him questions, and he engaged them in a discussion of the importance of system schema. He said, "The first place that students go awry is in identifying the system." Teachers said that system schema are valuable, take little time, and are do-able even by less adept students. In fact, some teachers said that slower students profit MOST by system schema.

David suggested having all students draw a system schema on whiteboards, then ask a few students to show them. If they've chosen different systems, their system schemas will be different and yet can be correct; this is instructive.

[Jane's note: I haven't transcribed any more, although David spoke for another 1/2 hour on this topic. To understand it, it is important that you study David's MODELING METHODOLOGY article, especially Box 5 there.]