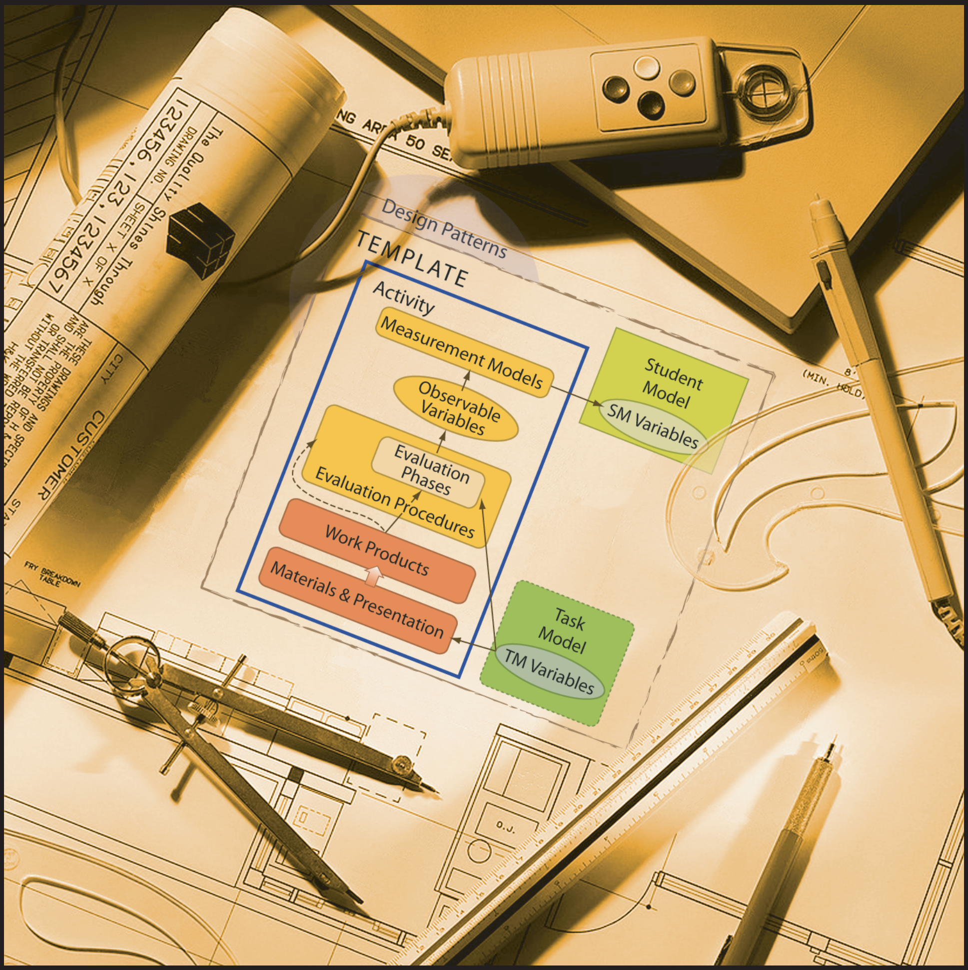

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Task Templates Based on Misconception Research

PADI | Principled Assessment Designs for Inquiry

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Task Templates Based on Misconception Research

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ABSTRACT

Researchers spend much time and effort developing assessments, including assessments of students' conceptual knowledge. In an effort to make such assessments easier to design, the Principled Assessment Designs for Inquiry (PADI) project has developed a framework for designing tasks and accompanying measurement models. One application of the PADI framework involves "reverse engineering" existing science assessments. This paper reports one such effort, motivated by assessments that elicit students' qualitative explanations of situations that have been designed to provoke misconceptions and partial understandings. We describe four task-specific *templates* we created—three based on Hestenes, Wells, and Swackhamer's (1992) Force Concept Inventory and one based on Novick and Nussbaums's (1981) Test about Particles in a Gas (TAP). We then describe an overarching framework for these *templates*, another PADI object called a *design pattern*, based on Stewart's concept of "Model Using." For each *template*, we describe a multivariate Student Model, a Measurement Model, and a Task Model. We conclude by suggesting how these *templates* and the *design pattern* could help researchers (and perhaps teachers) who wish to design new assessments in science domains where students are known to hold misconceptions.

1.0 Introduction

Creating tasks to assess underlying concepts and inquiry processes in science is not easy. The National Science Foundation has funded the Principled Assessment Designs for Inquiry (PADI) project, under the Interagency Educational Research Initiative (IERI), to create a conceptual framework and supporting software to help people design inquiry assessments. Among the data structures PADI has developed to this end are *design patterns*, which lay out assessment arguments at a conceptual level; *task templates*, which are schemas for the operational elements of an assessment and support the creation of families of related tasks; and *task specs* (short for "*task specification*"), which describe the elements of individual tasks in transportable formats—specifically, the Question and Test Interoperability (QTI) standards for electronic learning and assessment materials developed by the IMS Global Learning Consortium (n.d.) and extensions thereof.

One type of activity within the PADI project involves taking existing assessments used for science inquiry research and writing *templates* and *task specification* for those assessments. We refer to this process as "reverse engineering," in that the *templates* and *task specification* that are developed from existing tasks could be used to reproduce the same assessments or to produce new or analogous questions in the same or a similar domain. This report presents the results of applying reverse engineering to two conceptual assessments in science, the Force Concept Inventory (FCI; Hestenes et al., 1992) and the Test about Particles in a Gas (TAP; Novick & Nussbaum, 1981). Both assessments are based on research about student misconceptions, an area of cognitive psychology research on expert and novice performance.

Section 2.0 provides a brief review of the theoretical basis for these assessments in the novice-expert and misconceptions paradigms in cognitive psychology. Section 3.0 discusses the challenges that misconceptions research poses for assessment and the benefits of making available to researchers the type of *design patterns* and *templates* that PADI is producing. Section 4.0 summarizes the structure of PADI *task templates*. Section 5.0 discusses the development of a *design pattern* and *template* for the Force Concept Inventory, a conceptual assessment of knowledge about Newtonian physics. The Student Model, Evidence Model, and Task Model for the *template* are discussed. Section 6.0 describes the process of adapting the *template* for the Test about Particles in a Gas. Section 7.0 discusses a higher-level, less technical assessment design tool called a *design pattern* (Mislevy et al., 2003), which describes a general class of tasks like the FCI and TAP tasks, aimed at revealing student misconceptions. Section 8.0 closes with a summary of the potential benefits to users of the *design pattern* and of the four *templates* that were developed.

2.0 Novice-Expert Research

One of the dominant strains of cognitive psychology research from the mid-1970s through the 1980s was the study of expert performance across numerous domains (for reviews, see Charness & Schultetus, 1999; Ericsson & Charness, 1997). The basic premise of this line of research was that if the characteristics of expert performance could be isolated and identified, perhaps novices could be trained in the same specific knowledge, skills, and abilities to move them closer to expert performance. Moving away from previous notions of expertise as general and inborn, cognitive psychologists conducted research that led them to see expertise as domain specific and acquired through extensive teaching and practice (Ericsson & Smith, 1991; Ericsson, 1996). Whereas early expert-novice research tended to consider only expert performance (e.g., in chess, de Groot, 1946/1978), later research often contrasted experts and novices (e.g., in physics, Larkin, McDermott, Simon, & Simon, 1980). Early research also focused on problem-solving in domains with clearly delimited solutions and limited solution paths, called "well-defined domains" in the literature. Physics, chess, and medicine, in particular, were studied often, but other well-defined domains included occupations such as avionics technicians, waiters, and taxi drivers.

In physics, several researchers contrasted physics professors with typical undergraduate students. For example, Chi, Feltovich, and Glaser (1980) asked both physics professors and undergraduate students to sort various physics problems. Whereas the professors sorted the problems according to the physical laws that would be used to solve the problem (e.g., Newton's third law), novices tended to sort them according to physical features of the problem (e.g., pulley problems). In chess, Chase and Simon (1973) found that expert players were better able than novices to reconstruct the positions of chess pieces from memory, but only when the pieces were arrayed in actual game positions, not when they were placed randomly on the board. In medicine, Patel and Groen (1991) found developmental trends in medical expertise; whereas first-year medical students were not even aware that a written case contained irrelevant information, second-year students were distracted by that irrelevant information, while physicians recognized it as irrelevant.

In the course of developing a computer-based Intelligent Tutoring System (ITS) for military aircraft electronics technicians, Gitomer and colleagues found that expert technicians used a specific problem-solving strategy they termed "space splitting" (Steinberg & Gitomer, 1996). If there was an electrical fault in a line, expert avionics technicians would pick a halfway point between the power source and the inoperable part (e.g., a wing flap or aileron), and would test the circuit on both sides of the line. By continuing this process, they could quickly identify the malfunctioning electrical component. Novice technicians, by contrast, would use an inefficient process of checking each component in turn, one at a time. Ericsson and Polson (1988) found that the expert waiter whom they studied had developed detailed heuristics (e.g., males with certain builds were likely to order certain types of steaks) and mnemonics for remembering diners' orders. Expert taxi drivers studied by Chase (1982) used mental imagery to determine the quickest route from the current location to their destination.

These studies in well-defined domains established that expertise takes many years of guided practice to develop, that experts have a larger base of declarative knowledge than do novices, that their knowledge is better integrated and organized according to key principles in the domain, that experts know more domain-specific strategies, that their use of these strategies is automated, and that experts have more conditional knowledge about strategies (that is, they know in what situations to enact a particular strategy).

A later body of expert-novice research applied these findings to domains that do not have a single solution or finite set of solution strategies (called "ill-defined domains"), such as reading (e.g., reading law cases, Lundeberg, 1987; reading poetry, Peskin, 1998), history (e.g., Wineburg, 1991), teaching (e.g., Sabers, Cushing, & Berliner, 1991), and writing (e.g., Bruleux, 1991), with similar results.

Typically, researchers in novice-expert studies collect some sort of verbal report from participants, such as a think-aloud protocol (participants verbalize everything they are doing while performing a task), retrospective protocol (participants report after the fact what they think they were doing), or conduct an interview. A few methodologists have suggested that expertise researchers should simultaneously collect other process data, such as recording computer keystrokes, what participants are looking at (using eye-tracking devices), or reaction times (Ericsson & Smith, 1991; Magliano & Graesser, 1991). Researchers also have used other methods, such as the sorting task described above for Chi et al.'s (1980) physics expertise study.

One common finding across many expert-novice studies, especially in the sciences, is that novices often have specific mistaken ideas about particular domains. In one highly publicized example, 88% of graduating Harvard seniors surveyed believed that the seasons were caused by Earth's elliptical orbit around the sun, rather than by the tilt of the Earth on its axis (Gardner, 1999). Termed "misconceptions," these are ideas derived from daily experience that students bring to their learning experiences and that contradict scientific understandings and are often resistant to change.

Some other examples of misconceptions include: in biology, exercise makes breathing faster but shallower (e.g., Michael, 1998); in subtraction, subtract the smaller number from the larger, regardless of which number is being subtracted from (e.g., 725 – 569 = 244, since 7 – 5 = 2, 6 – 4 = 4, and 9 – 5 = 4, e.g., Brown & van Lehn, 1980); in history, textbooks are always correct and we can know "what happened" (e.g., Rouet, Britt, Mason, & Perfetti, 1996); in evolution, animal behavior changes offspring biology (that is, a Lamarckian belief; e.g., Bishop & Anderson, 1990); and in Earth science, the Earth is a globe with a flat top (e.g., Vosniadou & Brewer, 1992). Research about misconceptions thus has been a wide-ranging and productive field for cognitive science research, and one that has been frequently used in science inquiry research. This misconceptions research, however, has rarely been used to design assessments in a principled manner.

3.0 The Challenge for Assessment

Assessing students' learning in a way that reveals misconceptions poses considerable challenges for test designers. Students have many conceptions about any given domain, and some of these conceptions (i.e., misconceptions) can interfere with subject matter learning. However, research shows that students with misconceptions can nonetheless frequently correctly answer questions on traditional assessments. Physics students, for example, may be able to use algorithms to calculate answers to problems about which they have no conceptual understanding (e.g., Clement, 1983; Hunt & Minstrell, 1994). Assessments that are designed in light of the misconceptions literature, therefore, usually eschew calculation problems, on the grounds that these can be solved without having any conceptual understanding of the problem. In addition, because the purpose of assessing students' conceptions may be more diagnostic than normative, researchers (and teachers) may want to know which specific misconceptions students have (see Frederiksen & White, 1988). This type of use for assessment therefore requires different types of Measurement Models (and perhaps also Student Models) than does an end-of-semester physics examination used for assigning grades.

Researchers who are studying science inquiry also may be particularly interested in measuring conceptions, since inquiry activities (more so than didactic or cookbook lab approaches) may reveal students' misconceptions (e.g., Dalton, Morocco, Tivnan, & Mead, 1997; White & Frederiksen, 1998). However, developing psychometrically sound measurement instruments of science learning that reveal students' misconceptions is a difficult and time-consuming task, and one at which test developers are not always successful (see Cornely-Moss, 1995). Researchers who study science inquiry may be spending much time, energy, and resources "reinventing the wheel" as they develop measures for individual projects. In addition, researchers rarely have access to the kind of sophisticated statistics and technology that make both Student Models and statistical models more accurate and efficient. The goal of the PADI project is to address these needs by creating structures, including *design patterns* and *templates*, to help assessors organize their thinking about science learning into the shape of assessment arguments and tasks, and to illustrate their use in a variety of contexts. In this technical report, we present four *templates* and one *design pattern* that encompass misconception-based assessment in two science domains: Newtonian physics and gas laws.

4.0 PADI Design Patterns and Task Templates

PADI *design patterns* and *task templates* build on the evidence-centered assessment design (ECD) models of Mislevy, Steinberg, and Almond (2003). A good starting point is a quote from Messick (1994):

> A construct-centered approach [to assessment design] would begin by asking what complex of knowledge, skills, or other attributes should be assessed, presumably because they are tied to explicit or implicit objectives of instruction or are otherwise valued by society. Next, what behaviors or performances should reveal those constructs, and what tasks or situations should elicit those behaviors? Thus, the nature of the construct guides the selection or construction of relevant tasks as well as the rational development of construct-based scoring criteria and rubrics. (p. 16)

A PADI *design pattern* lays out, at a conceptual level, coherent sets of possibilities for the elements of the assessment argument outlined in the Messick quotation, organized around some aspect of scientific inquiry or conceptual knowledge. For example, there are the targeted knowledge, skills or abilities (targeted KSAs); things that students might say, do, or make that provide evidence of these KSAs (potential observations); and characteristic features of task situations in which these observations might be made. The *design pattern* structure is described and illustrated in detail in PADI Technical Report 1, Design Patterns for Assessing Science Inquiry (Mislevy et al., 2003). This brief description, however, should suffice to understand the example in Section 7.0.

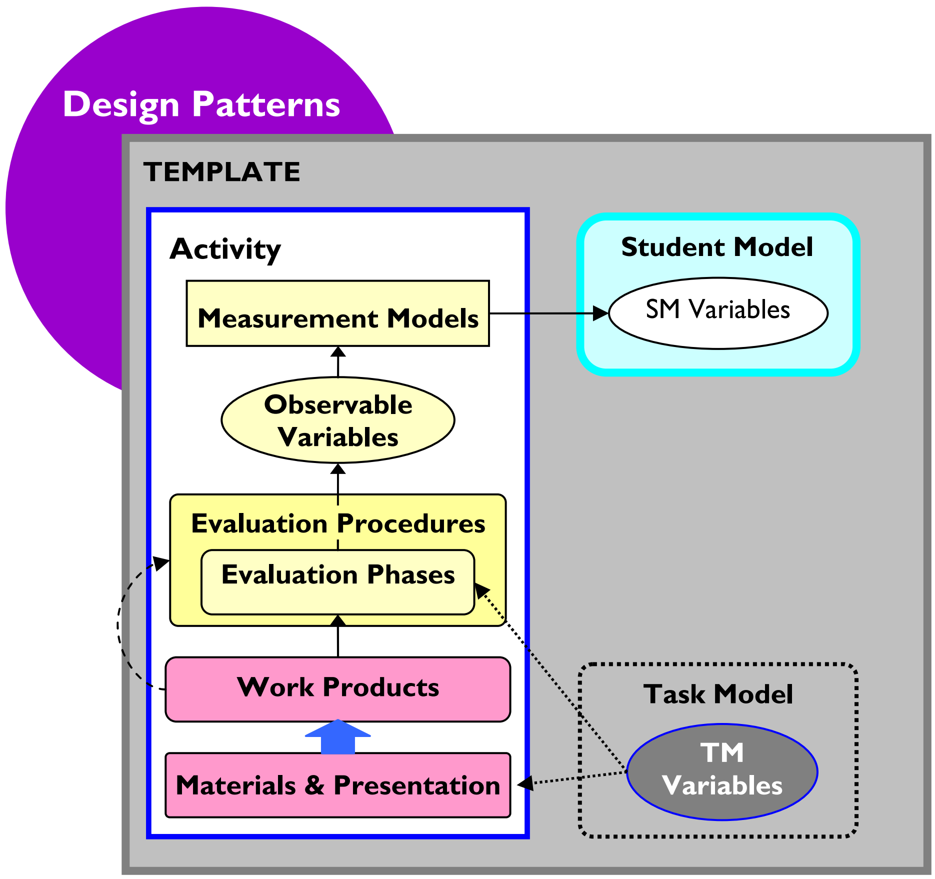
More attention is focused in this presentation on *task templates*. The reader is referred to PADI Technical Report 3, *An Introduction to PADI Task Templates* (Riconscente, Mislevy, Hamel, & PADI Research Group, 2005). *Task templates* are organized around three basic models in the Mislevy et al. (2003) evidenced-centered assessment framework—namely, the Student Model, the Evidence Model, and the Task Model:

- The Student Model contains variables that correspond to knowledge, skills, and abilities of an examinee about which inferences will be made—decisions about selection, placement, certification, instruction, task selection, and so on.
- The Evidence Model is a set of instructions for interpreting the response (Work Product) to a specific task. The Evidence Model contains two parts. The first is a series of Evaluation Procedures that describe how to identify and evaluate essential features of the Work Product. The second is a Measurement Model that tells how the belief about the Student Model Variables for a given student should be updated in light of the observed features of that student's responses.
- The Task Model is a generic description of a family of tasks. A Task Model contains (1) a list of variables that are used to describe key features of the tasks, such as their content, difficulty, and conditions under which they are presented; (2) a collection of Presentation Material specifications that describe the structure and format of material that will be presented to the participant as directions, stimulus, prompt, or instruction; and (3) a collection of Work Product specifications that describe the structure and format of traces of what the student will say, do, or make that will be

evaluated (e.g., item choices, sequence of solution steps, written explanations, videotapes of performances).

Figure 1 shows the constituent objects in a PADI *template*, which together encompass the Student, Evidence, and Task Models described above. The interested reader is referred to Riconscente et al. (2005) for detailed explanations of the structure of *templates*. This diagram, however, will help in understanding the examples of *templates* presented in the appendices, by indicating the hierarchical structure of the pieces that make up a *template*.

Figure 1: The Hierarchical Structure of PADI Templates



5.0 Illustrations from Newtonian Physics

One domain in which much work on misconceptions has been done is Newtonian physics. Several studies have shown that students can solve typical classroom quantitative problems in Newtonian physics, while failing to understand basic Newtonian principles (see, for example, DiSessa, 1993; White & Frederiksen, 1998; Clement, 1983). Newtonian motion problems can be divided into problems that consider an object moving in a horizontal plane (e.g., a hockey puck moving across ice), problems that concern only gravity acting on an object (either a still object or a moving object), and problems concerning horizontal motion and the vertical force of gravity acting simultaneously. A typical undergraduate physics assessment question asks whether students can correctly compute the time, distance, acceleration, or force needed to move an object:

> *A projectile is fired horizontally from a flare gun located 45.0 m above the ground. The projectile's speed as it leaves the gun is 250 m/s.*
>
> (a) How long does the projectile remain in the air?
>
> (b) What horizontal distance does the projectile travel before striking the ground?
>
> (c) What is its speed as it strikes the ground?
>
> (d) If the projectile were simply dropped from a height of 45.0 m, instead of fired horizontally from that height, how much time would it take to reach the ground? How does this compare with your answer to part (a)?

Note: From UC Berkeley Instructional Technology Program, 1994.

The following are common misconceptions in Newtonian physics:

- "Impetus," the pre-Newtonian notion that as long as a body is in motion, a force must be acting on it (McCloskey, 1983). Students may be able to correctly calculate the amount of force required to set a body in motion—e.g., to move a 10-kg box from rest—but they might believe that force is required to keep the box moving. In actuality, once the box has accelerated to its final velocity (assuming a frictionless world), no force is required to keep it in motion.

- Heavier objects exert more force (diSessa, 1993). (It does, of course, require more force to start a heavier object in motion.)

- Objects not at rest must have no forces acting on them (Clement, 1983). In actuality, when an object such as book sits on a table, gravity (a force) pulls down on the book, and the table pushes back up with exactly the same amount of force against gravity.

- Heavier objects fall faster than lighter ones (the belief tested in Galileo's perhaps apocryphal experiment at the leaning tower of Pisa).

- The "Wile E. Coyote" misconception—the notion that "Any body suspended in space will remain in space until made aware of its situation" (Hope, 1994).

- Falling objects that are also moving horizontally fall straight down or in right-angle or circular arcs. A student might be able to calculate the horizontal distance that an object travels but misunderstand that objects that move both horizontally at a constant speed and vertically under the force of gravity always move in a parabola.

5.1 The Force Concept Inventory

In 1992, David Hestenes and colleagues published a multiple-choice measure of students' conceptual knowledge of Newtonian physics called the Force Concept Inventory, or FCI (Hestenes et al., 1992). The FCI has been widely used as an undergraduate physics pre- and posttest to measure whether students truly understand motion or whether they can simply do calculations but lack a fundamental understanding. The FCI consists of 30 multiple-choice Newtonian physics problems that do not require any calculation but are designed to tap students' understanding of various aspects of Newtonian mechanics and circular motion. The measure was constructed by reviewing prior research on correct Newtonian conceptions and specific student misunderstandings. In the original publication, 23 specific Newtonian force concepts were listed (Hestenes et al., 1992, Table I) and used to construct correct options for the FCI. Additionally, 30 specific misconceptions were listed (Table II) and used to construct incorrect options for the same items. The Force and Motion Conceptual Evaluation (FMCE; Thornton & Sokoloff, 1998) is a similar assessment.

The following sections describe elements necessary for *task templates* that describe FCI-type tasks—that is, reverse-engineered *templates* that might be thought of as more general structures from which the actual tasks could have been derived. More substantive descriptions follow; PADI design system screen shots of actual PADI *templates* appear in the appendices.

5.2 Student Model

Hestenes and colleagues (1992) originally conceived of a univariate Student Model—students are Newtonian to either a greater or lesser extent (i.e., they answer more or fewer FCI questions correctly). Bao and Redish (2001) suggested an alternative interpretation: A student can be in multiple belief states (e.g., Newtonian reasoning; Galilean, or "impetus" reasoning; and nonscientific, including Aristotelian reasoning) simultaneously, applying one in any given situation with a probability that depends partly on the student's propensity to reason through each of the perspectives and partly on the features of the situation. The Student Model Variables characterize the students' propensities to reason through each of the perspectives. Task parameters, discussed below, characterize a task's tendency to evoke thinking through the same perspectives.

This approach is similar to other multivariate models used in developmental and cognitive psychology. For example, Robert Siegler (1976) has analyzed children's developing ability to solve problems in which different weights are put on either side of a balance beam. Children at the same stage of development may give different answers to the same balance beam problem, and children at different stages may give similar answers. However, overall, children in the same stage show a similar distribution of answers that are characteristic of their developmental stage. Thus, with the FCI we could imagine a student who answers like a Newtonian 70% of the time, like a Galilean 20% of the time, and in a nonscientific manner 10% of the time, recognizing that which kind of answer a student gives also depends on the features of the task at hand.

In the PADI design system, this Student Model has been named the "FCI-ish Student Model." Students have propensities to respond to tasks in a certain class (e.g., FCI and FMCE items) in terms of three specific conception models: Newtonian, Galilean, and nonscientific. Formally, each student *i* is characterized by a vector of three real numbers, (θ_{i1}, θ_{i2}, θ_{i3}), where higher numbers indicate a greater propensity toward a given response class—in this case, Newtonian, Galilean, and nonscientific. Statistically, the model can be made identified by implicitly fixing the sum of each examinee's three parameters at zero, or fixing the first parameter to zero. The latter approach is taken in the example illustrated here, so there are only two Student Model Variables to be estimated, those for the Galilean and nonscientific propensities.

5.3 Evidence Model

5.3.1 Evaluation Procedures and Evidence Rules

The FCI was originally a multiple-choice measure; evidence about the Student Model consisted of which multiple-choice option was chosen. With the multivariate Student Model approach we have taken in PADI, these evidence rules are expanded. Specifically, each multiple-choice option has been mapped to known Newtonian conceptions (Hestenes et al., 1992, Table I) and non-Newtonian misconceptions (which are further subdivided into the Galilean and nonscientific misconceptions contained in Table II). Although we have chosen to analyze the FCI in its original multiple-choice format, it would be easy to adapt it for open-ended responses, which would be coded. These codes would then be mapped to specific conceptions. We will see later that just this approach was taken by the designers of an analogous measure, the Test about Particles in a Gas (TAP; Novick & Nussbaum, 1981).

5.3.2 Measurement Model

The Measurement Model for the FCI was originally a simple additive model. A multivariate statistical model for the FCI was recently investigated by Huang (2003) in dissertation research. Huang used an Andersen/Rasch (A/R) multivariate model (Andersen, 1973), in which a student is seen as being in several belief states, each with a certain propensity, and each FCI question is seen as evoking belief states, each question with a certain tendency to evoke responses of the different types.

The A/R model takes the following form for a situation in which there are *m* response types and student and task parameters that correspond to them. Let X_{ij} ($i = 1, \ldots, n$: $j = 1, \ldots, k$) be independent observable random variables (*i* is the index for examinees, *j* is the index for items), where X_{ij} can be any integer between 1 and *m*. The probability that the response X_{ij} that student *i* produces for task *j* is of type *p* is given as

$$P(X_{ij} = p) = \exp(\theta_{ip} + \beta_{jp}) / \sum_{p=1}^{m} \exp(\theta_{ip} + \beta_{jp}),$$

where:

p is an integer between 1 and *m*, indicating response class;

θ_{ip} is the *p*th element in person *i*'s vector-valued parameter; and

β_{jp} is the *p*th element in item *j*'s vector-valued parameter.

Note that there are *m* probabilities for each examinee on a given item, representing the probability of that person's making any particular choice on that item.

The Andersen/Rasch model can be written as a special case of the Multidimensional Random Coefficients Multinomial Logit Model (MRCMLM) used by the PADI project (Adams, Wilson, & Wang, 1997). For more information, see Huang (2003).

5.4 Task Models

In the PADI design system, we have created four *task templates* related to misconception research. All have the same Student and Evidence Model structures but differ as to the Task Models. Three Task Models are for particular types of FCI problems (Hestenes et al., 1992), and one is for the TAP (Novick & Nussbaum, 1983). In these Task Models, we do not create new items or content that goes beyond the work done by the authors of the measures. Rather, we write a more general set of *task template* structures (similar to item specifications) that can enable researchers—and perhaps teachers—to create analogous measures in their own domains of interest.

The three *templates* for FCI-type problems correspond to (a) problems involving only gravity and no horizontal motion, which we refer to as G Problems; (b) problems involving only horizontal motion, which do not tap students' knowledge of gravity, which we refer to as H Problems; and (c) problems that tap students' knowledge of both horizontal motion and gravity, which we call H & G Problems.

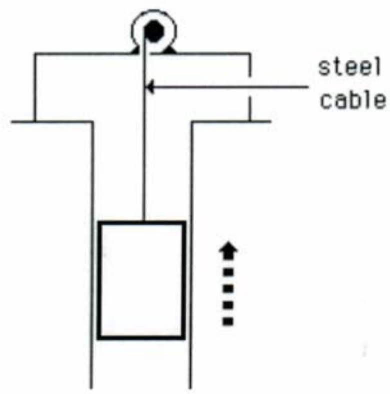
5.4.1 G Problems

A typical G Problem from the FCI is shown in Figure 2. The *template* titled Force Problems—Gravity Only refers to the state of motion of the object (up, down, or no motion), the duration of motion, friction, the identity of the vertical force (e.g., gravity, the force of an elevator cable pulling up), whether or not there is an illustration used in the problem, the mass and identity of the object being moved, the speed at which the object is being moved, and the time period of interest (e.g., how long it takes an object to fall). (Appendix A presents *templates* and related *task specification* for Force Problems—Gravity Only.) For example, the problem shown in Figure 2 involves the continuous upward motion of an elevator at an unspecified speed, no friction, the upward force of the elevator cable, the downward force of gravity, and an illustration.

Figure 2: An FCI Problem That Tests Students' Knowledge of Gravity But DoesNot Involve Horizontal Motion

17. An elevator is being lifted up an elevator shaft at a constant speed by a steel cable as shown in the figure below. All frictional effects are negligible. In this situation, forces on the elevator are such that:

(A) the upward force by the cable is greater than the downward force of gravity.
(B) the upward force by the cable is equal to the downward force of gravity.
(C) the upward force by the cable is smaller than the downward force of gravity.
(D) the upward force by the cable is greater than the sum of the downward force of gravity and a downward force due to the air.
(E) none of the above. (The elevator goes up because the cable is being shortened, not because an upward force is exerted on the elevator by the cable).



Elevator going up
at constant speed

Note. From "Force Concept Inventory," by D. Hestenes, M. Wells, & G. Swackhamer, 1992, The Physics Teacher, 30, pp. 141-158. Reprinted with permission.

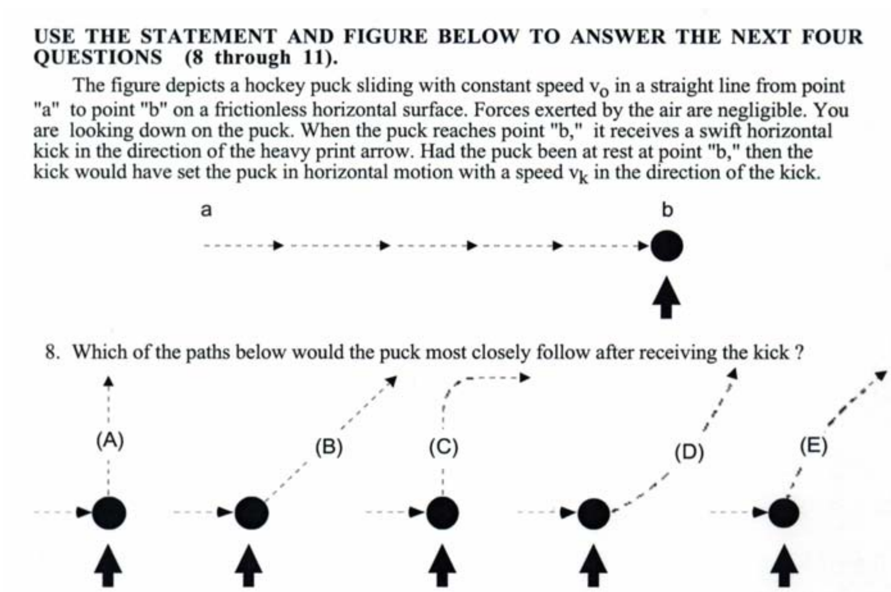
Some of these Task Model Variables are important in describing incidental features of the task situation, which may be varied to provide a range of tasks that are different on the surface but similar as to the thinking they tend to evoke. The identity of the object is such a variable. Other Task Model Variables are important because they characterize features that are linked to common misconceptions. State of motion—whether an object is at rest, moving up, or moving down—is an example of this type. Many students believe that when an object is at rest, there are no forces acting on it.

G Problems in the FCI ask about the forces acting on an elevator being pulled up a shaft, a steel ball that has been tossed straight up, a stone dropped from the roof of a building, a tennis ball at an instant after it has been hit, a metal ball at an instant inside a tube, and an office chair at rest on a floor. This particular *template* helps a researcher to create more FCI-like G Problems. The researcher creates a situation of the kind described in the Task Model and describable by the Task Model Variables. For multiple-choice tasks like those on the FCI, options are constructed by giving one or more predictions or explanations for the situation, each consistent with Newtonian reasoning, with Galilean impetus reasoning, or with nonscientific (e.g., Aristotelian) reasoning. As illustrated in Section 7.0, one can reason by analogy to another science domain in which students have misconceptions to create one or more new *templates* from which to develop an entirely new measure.

5.4.2 H Problems

A typical H Problem from the FCI is shown in Figure 3. The *template* titled Force Problems—Horizontal refers to the identity, direction, amount, and duration of force applied; the mass and identity of the object being moved; whether an illustration is included; the speed and direction of the object being moved; and the time period of interest (before, during, or after the force is applied). (See Appendix B for the Force Problems—Horizontal *template*.) Note that the G Problem and H Problem *templates* have seven Task Model Variables in common: the direction of motion, duration, friction, the identity of the force applied, whether an illustration is included, the mass of the object being moved, and the time period of interest. For example, the problem shown in Figure 3 involves an instantaneous "kick" of unspecified force delivered at right angles to the direction of motion of a hockey puck; the puck's speed and mass are not specified (although we can assume it is lighter than, say, a rocket); we are told to imagine a frictionless situation; and the problem is illustrated.

Figure 3: An FCI Problem That Tests Students' Knowledge of Horizontal Motion But Does Not Involve Gravity


USE THE STATEMENT AND FIGURE BELOW TO ANSWER THE NEXT FOUR QUESTIONS (8 through 11).

The figure depicts a hockey puck sliding with constant speed v_o in a straight line from point "a" to point "b" on a frictionless horizontal surface. Forces exerted by the air are negligible. You are looking down on the puck. When the puck reaches point "b," it receives a swift horizontal kick in the direction of the heavy print arrow. Had the puck been at rest at point "b," then the kick would have set the puck in horizontal motion with a speed v_k in the direction of the kick.

8. Which of the paths below would the puck most closely follow after receiving the kick ?

Note. From "Force Concept Inventory," by D. Hestenes, M. Wells, & G. Swackhamer, 1992, The Physics Teacher, 30, pp. 141-158. Reprinted with permission.

Task model variables that are particularly important in eliciting misconceptions are the direction and duration of the force. Table 1 shows examples of how certain combinations of task model variables for a Newton's third law problem ("for every action there is an equal and opposite reaction") can tend to elicit specific conceptions or misconceptions (see Hammer & Elby, 2003).

Table 1: Conceptions That Tend to Be Provoked by Combinations of Task Model Variables

		Object That Does the Hitting	
		Light	Heavy
Object That Gets Hit	Light	Correct Newtonian conception	Misconception of more force from the heavier object
	Heavy	Misconception of more force from the heavier object	Correct Newtonian conception

		Object That Does the Hitting	
		Slow	Fast
Object That Gets Hit	Slow	Correct Newtonian conception	Misconception of more force from the faster object
	Fast	Misconception of more force from the faster object	Correct Newtonian conception

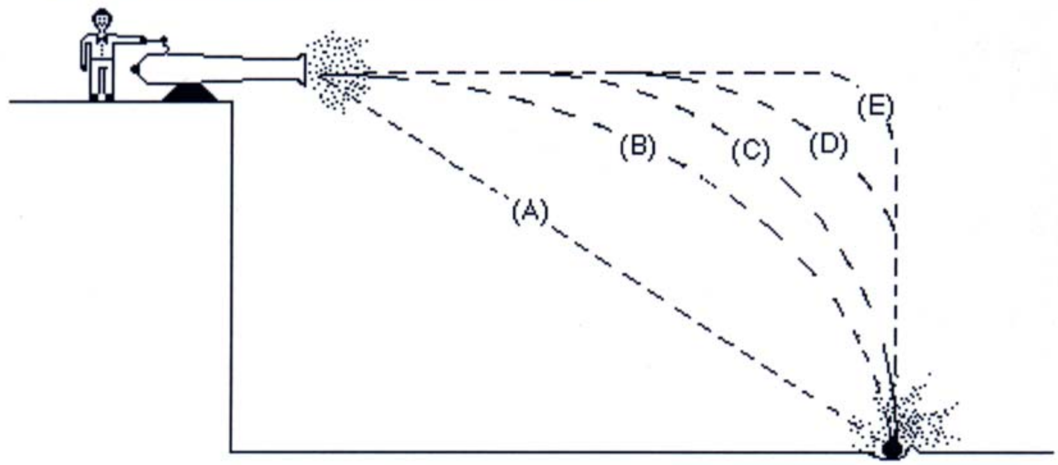
H problems in the FCI ask about a hockey puck that receives a kick, a rocket in space whose engine turns on, a car that is pushing a truck, a truck that collides with a car, a woman pushing a box, and two students on office chairs who push away from each other. This *template* likewise would help a researcher create more FCI-like H Problems or to create a new measure.

5.4.3 Force Problems—Horizontal and Gravity

The third Task Model we created was for more complex problems that require students to apply their knowledge of both horizontal motion and the effect of gravity. A typical H & G Problem from the FCI is shown in Figure 4. The *template* titled Force Problems—Horizontal and Gravity (see Appendix C) refers to the identity, direction, and amount of force applied; the mass and identity of the object being moved; whether an illustration is included; the direction of motion; and the shape of the path of motion of the object being moved. Note that several task model variables from the G Problem and H Problem *templates* are missing from this more complex *template*: the duration of force applied, the speed and direction of the object; the mass, size, and identity of the object; and the time period of interest (before, during, or after force is applied). For example, the problem shown in Figure 4 involves the instantaneous force of a cannon (the amount of force is not specified) shooting a (presumably heavy) cannonball; the shot is made in a forward direction parallel to the ground; the question asks examinees to determine the shape of the path of motion; and an illustration is included.

Figure 4: An FCI Problem That Tests Students' Knowledge of Both Horizontal Motion and Gravity

12. A ball is fired by a cannon from the top of a cliff as shown in the figure below. Which of the paths would the cannon ball most closely follow?



Note. *From "Force Concept Inventory," by D. Hestenes, M. Wells, & G. Swackhamer, 1992, The Physics Teacher, 30, pp. 141-158. Reprinted with permission.*

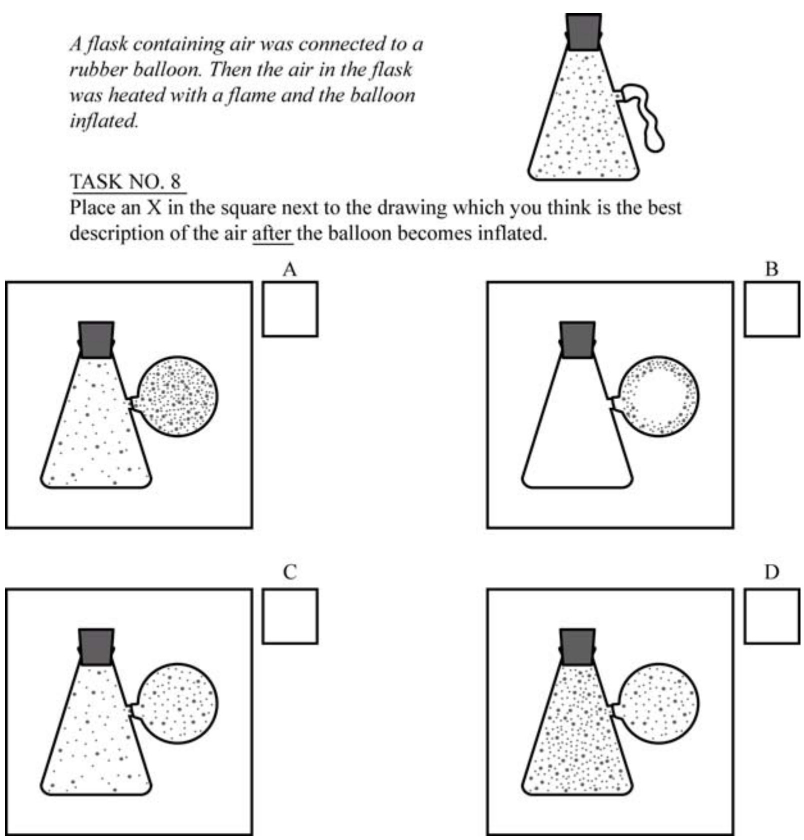
H & G Problems in the FCI ask about a cannonball shot out of a cannon, balls rolling off a cliff, a bowling ball dropped from a flying airplane, and a tennis ball hit into the wind. Similar to the other two *templates*, this *template* would allow a researcher to create more FCI-like H & G Problems or to create a new measure.

6.0 Illustrations from Gas Laws

A second scientific domain in which students have been shown to hold misconceptions is the gas laws—systematic relationships among the pressure, volume, and temperature of gases in closed containers. Some misconceptions that have been observed include the notion that in a partial vacuum gases "rise to the top" or "sink to the bottom" of their container (see Benson, Wittrock, & Baur, 1993; Lin, Cheng, & Lawrenz, 2000; Mas, Perez, & Harris, 1987; Meheut, 1997). On the basis of several interview studies, Novick and Nussbaum (1978, 1981) identified five core beliefs that make up a scientific conception of gas behavior: that gases are made up of particles; that there is empty space between the particles; that the particles are uniformly distributed in a closed container; that the particles are in constant motion, and that when a gas becomes a liquid, there is a change in the density of the collection of particles.

Novick and Nussbaum (1981) constructed the Test about Particles in a Gas (TAP), a noncomputational measure of students' conceptual knowledge about gas behavior. It is an eight-question measure combining multiple-choice questions with drawing tasks and other constructed-response questions that are scored by coders into conceptual categories. A sample problem from the TAP is shown in Figure 5.

Figure 5: A TAP Problem That Tests Students' Knowledge of the Molecular Theory of Gases



Note. From "Pupils' understanding of the particulate nature of matter: A cross-age study," by S. Novick & J. Nussbaum, 1981, Science Education, 65(2), 187-196.

Like the FCI, the TAP is designed to reveal students' conceptions about how gases behave, not to test their ability to compute typical gas law problems. For contrast, a typical high school assessment question asks whether students can correctly compute the mass, volume, or pressure of a gas under certain conditions, or to identify a gas given information about its temperature, volume, and pressure:

> 105. 1.09 g of H2 is contained in a 2.00 L container at 20.0 °C. What is the pressure in this container in mm Hg?
>
> 118. Determine the number of grams of carbon dioxide in a 450.6 mL tank at 1.80 atm and minus 50.5 °C. Determine the number of grams of oxygen that the same container will contain under the same temperature and pressure.
>
> 132. If 9.006 grams of a gas are enclosed in a 50.00 liter vessel at 273.15 K and 2.000 atmospheres of pressure, what is the molar mass of the gas? What gas is this?

Note: Selected gas law problems from Diamond Bar High School, Walnut Valley Unified School District, CA (Park, 1996)

As with the FCI, we "reverse engineered" a design *template* for constructing a TAP-like assessment that uses the research base about student misconceptions to develop a principled assessment (see Appendix D).

6.1 Student Model

As with the FCI, we propose that students can be seen as being in multiple belief states, each with a certain propensity. For example, students might simultaneously believe that particles in a gas are uniformly distributed in a closed container and also believe that particles are non-uniformly distributed, each with a certain propensity. As with the FCI, the original Student Model was a simple univariate model (students are characterized as either scientific or nonscientific).

6.2 Evidence Model

Because the TAP includes both multiple-choice and constructed-response questions, its Evidence Model is more complicated than those of the three FCI *templates*.

6.2.1 Evaluation Procedures and Evidence Rules.

The evidence rules for multiple-choice items on the TAP are analogous to those for the FCI Evidence Models—evidence about the student corresponds to which multiple-choice option was selected. For constructed-response items, however, the responses must be coded by a coder into *a priori* categories that correspond to model classifications that are mapped onto Novick and Nussbaum's (1981) five principles—that is, coded in terms of correct understandings or misunderstandings that are keyed to one or more of the five targeted principles. For example, when students make a drawing of gas in a container, coders have to rate the drawing as showing a particulate vs. continuous conception of gases (see also Benson et al., 1993).

6.2.2 Measurement Model

We propose that the Andersen/Rasch Measurement Model (Andersen, 1995) could likewise be applied to the TAP. Each student would be modeled as being in several belief states, each with a certain propensity; each problem would also be seen as provoking certain belief states, each with a certain propensity. As with the FCI, the original statistical model for the TAP was a simple additive model.

6.3 Task Model

The Task Model for TAP questions has two variables in common with the FCI Task Model: whether an illustration is used and the nature of the substances involved in the problem. Many of the task model variables are similar to those that would be used in a conventional calculation problem (e.g., pressure, volume, and temperature in a closed system); however, TAP problems never give numerical quantities (similar to FCI problems). As in the FCI, students make predictions about or explanations of gas behavior. Interestingly, Novick and Nussbaum (1981) found that problem number 8 (shown in Figure 5) was often answered incorrectly, even by students who demonstrated a correct conception of uniform distribution of gases in a rigid container. An additional task model variable is therefore the rigidity of the container (e.g., a rigid glass container vs. a flexible balloon). TAP problems also vary the response format (e.g., multiple choice vs. drawing). As with the FCI and mechanics principles, each TAP problem links to only one of the five scientific gas principles.

7.0 A General Design Pattern

We see the three FCI *templates* (H, G, and H & G) and the TAP as instantiations of a general type of scientific reasoning that Stewart refers to as "Model Using" (Stewart & Hafner, 1994; Stewart, Hafner, Johnson, & Finkel, 1992; see Appendix E). In Model Using, students reason through a given model about a scientific problem. These problems do not present anomalous data that challenge students' existing models; rather, they provide practice on applying targeted scientific models. In Model Using, students may consolidate their understanding of a model and how to apply it to problems.

Model Using is itself an instantiation of a general class of scientific reasoning involving models, called "model-based reasoning." In addition to Model Using, Stewart and colleagues have identified Model Elaboration and Model Revising (Stewart & Hafner, 1994). Model Elaboration and Model Revising differ from Model Using primarily in that these types of reasoning involve anomalous data that do not fit students' existing models. Model Using, on the other hand, involves practice in applying a model to a situation that does not contradict the targeted model.

We see Model Using as a flexible *design pattern* that can encompass student reasoning with both correct (i.e., scientific) and partially correct (e.g., DiSessa's [1993] "p-prims") models. Model Using requires knowledge of a model, but especially conditional knowledge about when the model can be applied to a situation (see also Larkin & Simon, 1987). In addition, students need domain-specific or general knowledge to use models. Students can use knowledge of the model and their domain-specific knowledge together to make predictions about and explanations of phenomena that the model applies to. For example, given a model of gravity as a force that pulls objects downward and general knowledge about elevators (e.g., that they are heavy, that they are attached to cables that are moved by pulleys), students can reason through their gravity model to make predictions about or explanations of the motion of an elevator (e.g., they could predict that if the elevator cable were cut, the elevator would fall because of gravity).

The FCI and TAP *templates*, in addition to using Model Using, also depend on a preexisting body of research that has identified student misconceptions for a particular domain. These are required in order to construct distractors that will appeal to students who do not hold scientific conceptions. For example, the TAP distractors were chosen on the basis of Novick and Nussbaum's (1978) interview study; the FCI distractors were built from a large body of prior studies by researchers such as Clement (1983), Frederiksen and White (1988), Hunt and Minstrell (1994), McCloskey (1983), and others. *Templates* could specifically point to misconceptions that could be used to construct distractors.

8.0 Final Comments

The ultimate goal of the *design pattern* and *task templates* is that researchers, teachers, and test developers can have worked-out samples of assessments that are theory based, psychometrically sound, and less burdensome than a “reinvent the wheel” approach, and that make optimal use of technology. For example, the Model Using *design pattern* and the four associated *templates* developed here are based on research on students’ misconceptions in science—one application of the novice-expert paradigm in cognitive psychology. These filled-in PADI task design structures are able to take a significant part of the assessment development burden off of task designers, whether they choose to use the *templates* as is or adapt them.

Tasks developed from these *templates*, such as the illustrations above or new ones built around the same design structures, are grounded in a branch of cognitive research in science learning. They could be developed either for informal use in the classroom or for larger-scale and more formal use with psychometric models. In assessment systems that follow this latter route, the *templates*’ theory-based Student Models and aligned Evidence Models are psychometrically sound. They take advantage of sophisticated statistical models (e.g., Rasch models, Bayes nets) that need not be developed afresh and the details of which can be made invisible to the task designer and end user. Finally, because PADI *templates* can be expressed in transportable form (specifically, they can be represented in XML format), they are simple to share and access via the Web and to use in systems that take advantage of automated student record keeping, adaptivity, and other technological features.

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APPENDIX A

PADI Template for Force Problems—Gravity Only

Appendix A

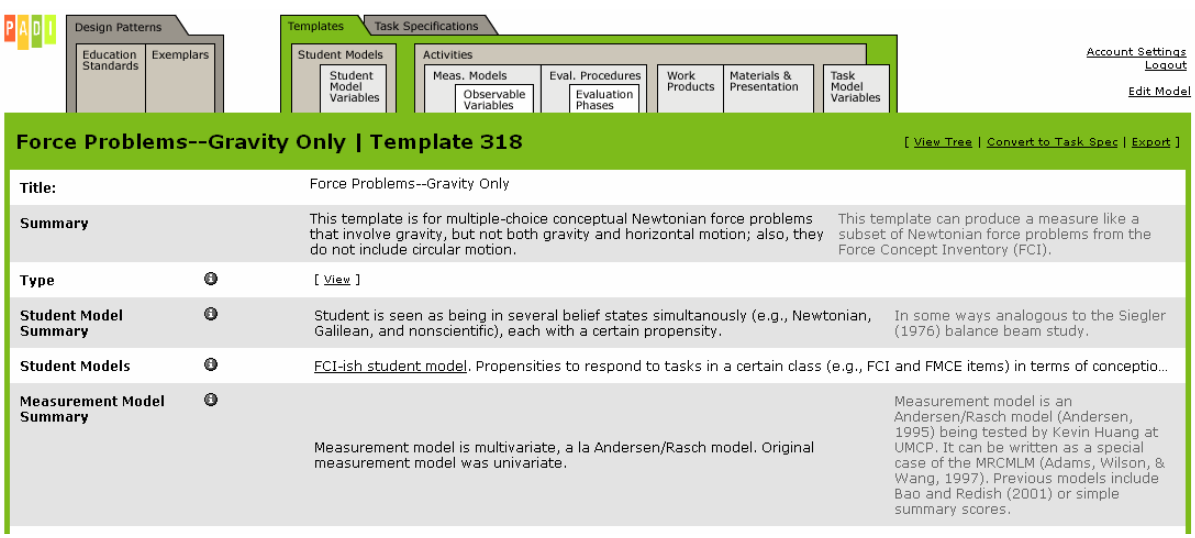
The PADI *template* for "Force Problems—Gravity Only" is reproduced below. The first illustration shows the top layer of the *template*. It provides an overview of all of the objects in the hierachically organized schema (see Figure 1 of the text). The seven following illustrations show lower layers in the *template* that are linked to the top layer. They specify, in turn, information about the Student Model, the Measurement Model, and the Task Model. The Student Model information is briefly described in the "Student Model Summary" section in the top layer, and detailed in the subsequent linked section that gives fuller details about the Student Model. The summary explains the multivariate Student Model proposed above, while the linked Student Model section defines in detail the model identification and the covariance matrix.

Measurement Model information is briefly described in the top layer's "Evaluation Procedures Summary" (evidence rules) and "Measurement Model Summary" (statistical model) sections. In more detailed sections of the *template*, the Evaluation Procedures explain the mapping of the multiple-choice items to Newtonian, Galilean, and nonscientific conception categories. The Measurement Model explains the Andersen/Rasch model.

Task Model information is briefly described in the top layer's "Activities," "Activity Sequencing," "Template-level Task Model Variables," and "Task Model Variable Settings." The primary activity for this *template* is "Make explanations and predictions from a physical situation," which is linked to the *template*. The Task Model Variables are linked to this particular *template*, with *template*-specific comments (e.g., the "Direction of Motion" Task Model Variable in this *template* is always vertical).

In addition, the *template* includes links to the Model Using *design pattern*, relevant research, Web resources (e.g., the Web site for the FCI), and other print resources, such as the Bao and Redish (2001) paper.

Figure A-1: PADI *Template* "Force Problems—Gravity Only"

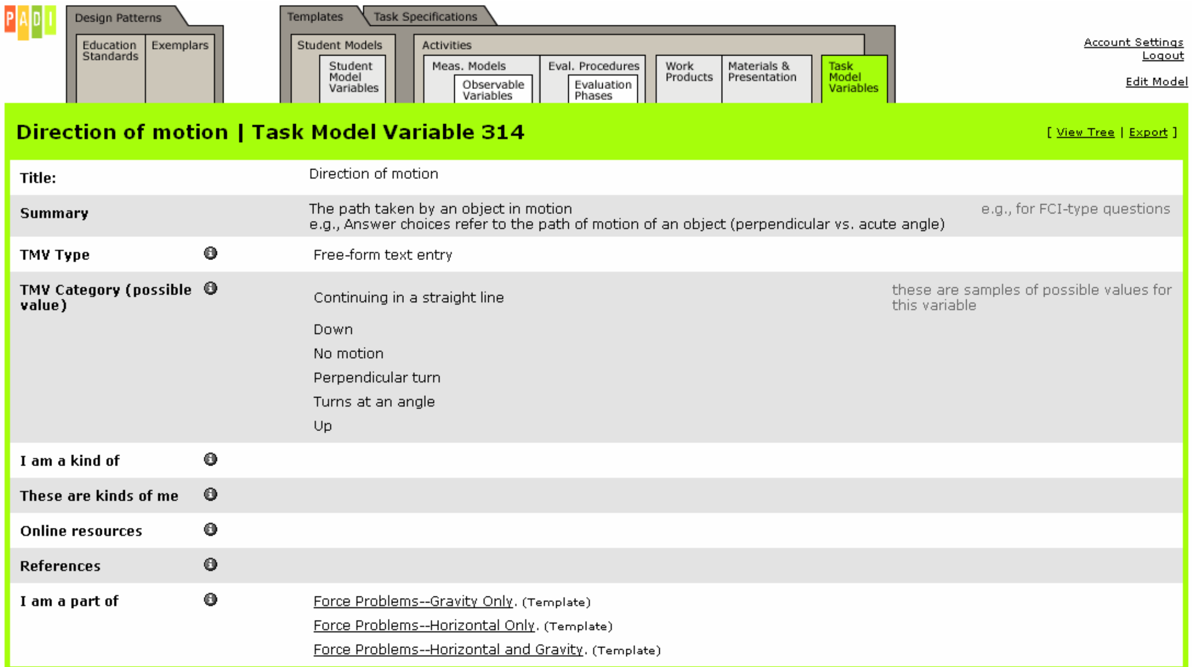


(continued)

Figure A-1: PADI *Template* "Force Problems—Gravity Only" *(continued)*

Evaluation Procedures Summary	Answer key--one correct answer per question.	Correct answer always corresponds to the result of reasoning from a Newtonian conception. (In principle, could have open-ended answers, which would be mapped into model categories--e.g., Minstrell, 1989)
Work Product Summary	Answers to multiple-choice problems are main work product.	Multiple choice responses have been constructed so that each one a priori maps to exactly one of the model classifications. Correct answers apply Newtonian principles correctly to the problem. Incorrect answers reflect non-Newtonian principles; specifically, misconceptions identified in prior literature, which might be Galilean, Aristotelian, or nonscientific. The list of Newtonian concepts tested in the FCI is listed in Hestenes, Wells & Swackhamer (1992), Table I. The list of common misconceptions used to construct distractors is listed in Table II of the same paper.
Task Model Variable Summary	Task model variables include direction of motion (up, down, or no motion); time elapsed; mass of object; forces other than gravity.	Downward force always = g = 32 ft/sec^2, friction always = 0, and Motion is always in a vertical plane in this subset of problems. Ex: FCI Q1 direction of motion = down time elapsed = (>, =, <) mass of object = same for both objects Ex: FCI Q17 direction of motion = up forces other than gravity = force of cable opposite to force of gravity. Irrelevant to this Q: time elapsed, mass of object
Template-level Task Model Variables	Direction of motion. The path taken by an object in motion e.g., Answer choices refer to the path of motion of an ob... Duration. e.g., in FCI-type problem, is a force applied instantaneously or over a period of time. Friction. Amount of friction between two objects such as a puck and ice, a rope and a pulley, a ball and air. Identity of horizontal force. The identity/ies of a force(s) which act(s) on an object(s) for an instant or over a period of time,... Illustrations. Whether or not an illustration (e.g., line drawing, photograph, video clip) is part of the task. Mass. e.g., Mass of object to which force is applied. Objects. Objects on which forces act. They may vary in size, mass, animate/inanimate, etc. Speed. e.g. The speed of an object at the moment when a force is applied to it. Time period of interest. Past, present, or future. e.g., Question asks about motion or speed while a force is applied vs. af...	
Task Model Variable Settings	[View]	
Materials and Presentation Requirements	Paper-and-pencil measure.	Could easily be adapted for computer administration.
Template-level Materials and Presentation		
Materials and Presentation Settings	[View]	
Activities Summary	Sets of questions relating to a single situation may be presented or answered in any order. Ordinarily all questions on the FCI are administered at one sitting (it is commonly used as a pretest-posttest measure in university introductory physics courses).	
Activities	Make explanations and predictions from a physical situation. Given a physical situation with some underlying regularities (e.g., a Newtonian law or gas law), stu...	
Tools for Examinee	Pen or pencil.	
Exemplars	Force Concept Inventory (FCI). A multiple-choice measure of students' conceptual knowledge of forces, including Newton's 1st-3rd la...	
Educational Standards		
Design Patterns	Model Using. This design pattern generates tasks where the student has to reason through a given model using data...	
I am a kind of		
These are kinds of me		
These are parts of me		
Online resources	FCI available at http://modeling.la.asu...	
References	Bao, L., & Redish, E.F. (2001). Model analysis: Assessing the dynamics of student learning. Wang (2003)	Available on the World Wide Web at http://www.physics.ohi...
I am a part of		

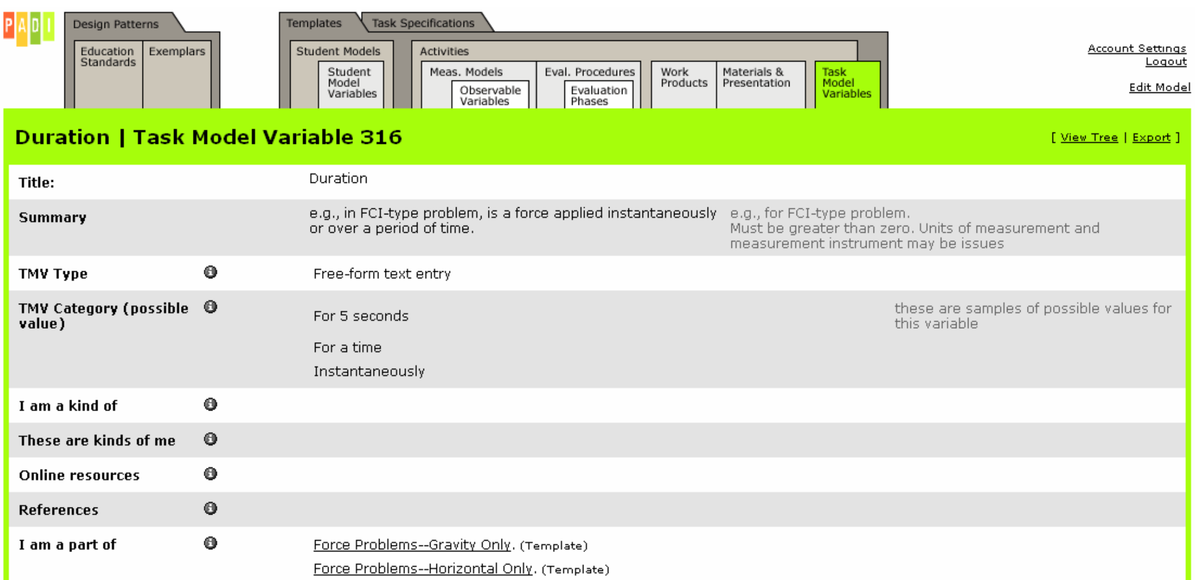
Figure A-2: PADI *Task Model Variable* "Direction of Motion"



Direction of motion | Task Model Variable 314 [View Tree | Export]

Title:	Direction of motion	
Summary	The path taken by an object in motion e.g., Answer choices refer to the path of motion of an object (perpendicular vs. acute angle)	e.g., for FCI-type questions
TMV Type	Free-form text entry	
TMV Category (possible value)	Continuing in a straight line Down No motion Perpendicular turn Turns at an angle Up	these are samples of possible values for this variable
I am a kind of		
These are kinds of me		
Online resources		
References		
I am a part of	Force Problems--Gravity Only. (Template) Force Problems--Horizontal Only. (Template) Force Problems--Horizontal and Gravity. (Template)	

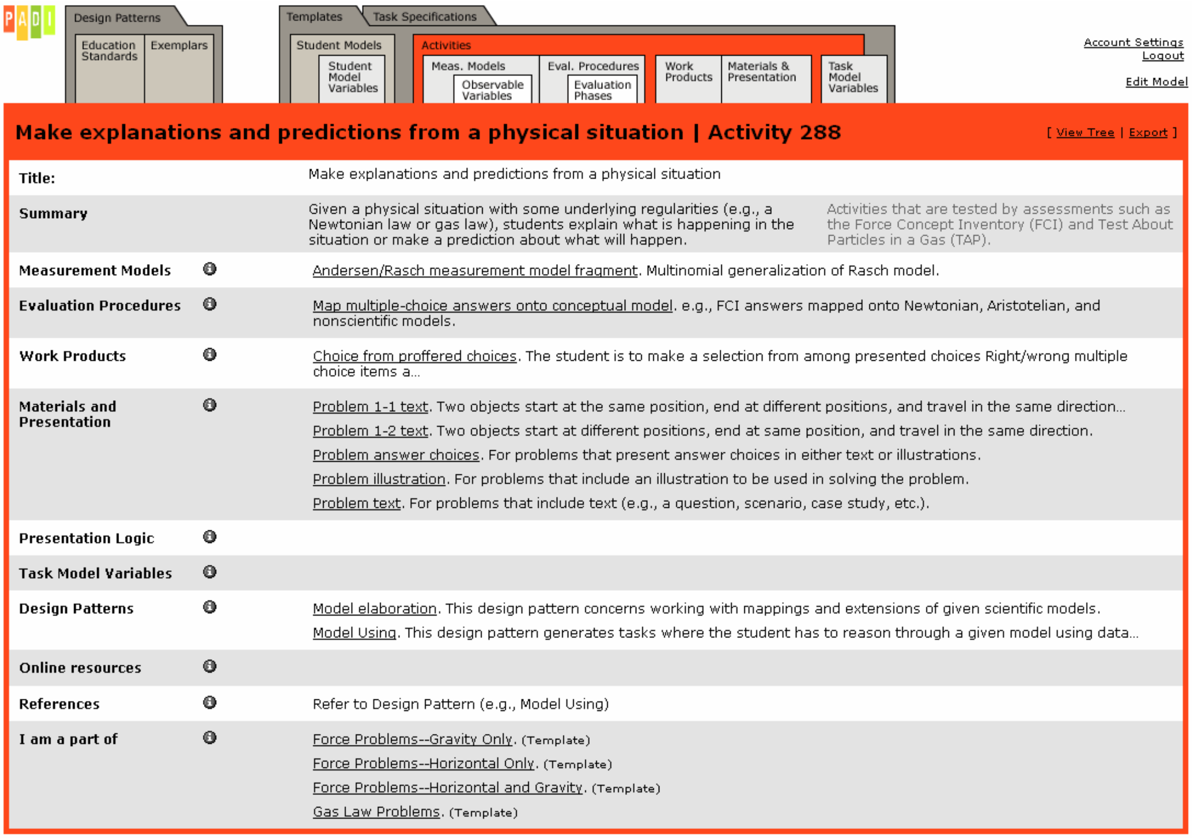
Figure A-3: PADI *Task Model Variable* "Duration"



Duration | Task Model Variable 316 [View Tree | Export]

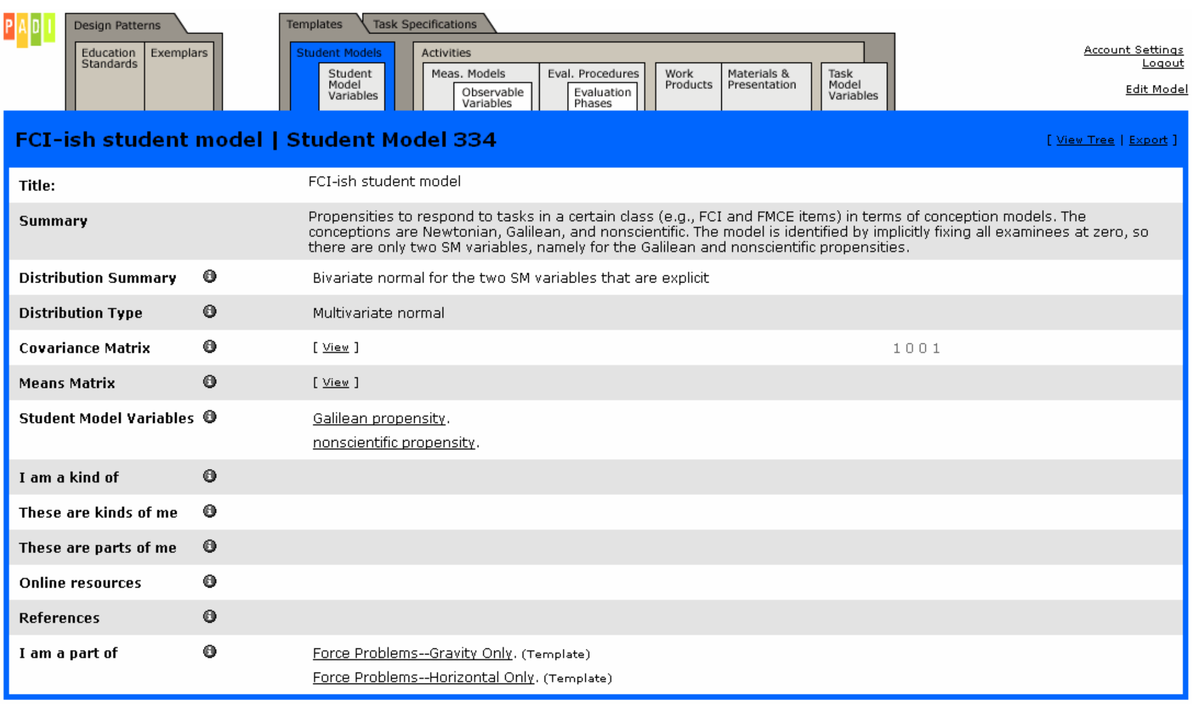
Title:	Duration	
Summary	e.g., in FCI-type problem, is a force applied instantaneously or over a period of time.	e.g., for FCI-type problem. Must be greater than zero. Units of measurement and measurement instrument may be issues
TMV Type	Free-form text entry	
TMV Category (possible value)	For 5 seconds For a time Instantaneously	these are samples of possible values for this variable
I am a kind of		
These are kinds of me		
Online resources		
References		
I am a part of	Force Problems--Gravity Only. (Template) Force Problems--Horizontal Only. (Template)	

Figure A-4: PADI *Activity* "Make Explanations and Predictions from a Physical Situation"



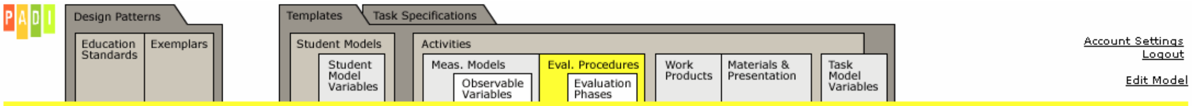
Title:	Make explanations and predictions from a physical situation
Summary	Given a physical situation with some underlying regularities (e.g., a Newtonian law or gas law), students explain what is happening in the situation or make a prediction about what will happen. — Activities that are tested by assessments such as the Force Concept Inventory (FCI) and Test About Particles in a Gas (TAP).
Measurement Models	Andersen/Rasch measurement model fragment. Multinomial generalization of Rasch model.
Evaluation Procedures	Map multiple-choice answers onto conceptual model. e.g., FCI answers mapped onto Newtonian, Aristotelian, and nonscientific models.
Work Products	Choice from proffered choices. The student is to make a selection from among presented choices Right/wrong multiple choice items a...
Materials and Presentation	Problem 1-1 text. Two objects start at the same position, end at different positions, and travel in the same direction... Problem 1-2 text. Two objects start at different positions, end at same position, and travel in the same direction. Problem answer choices. For problems that present answer choices in either text or illustrations. Problem illustration. For problems that include an illustration to be used in solving the problem. Problem text. For problems that include text (e.g., a question, scenario, case study, etc.).
Presentation Logic	
Task Model Variables	
Design Patterns	Model elaboration. This design pattern concerns working with mappings and extensions of given scientific models. Model Using. This design pattern generates tasks where the student has to reason through a given model using data...
Online resources	
References	Refer to Design Pattern (e.g., Model Using)
I am a part of	Force Problems--Gravity Only. (Template) Force Problems--Horizontal Only. (Template) Force Problems--Horizontal and Gravity. (Template) Gas Law Problems. (Template)

Figure A-5: PADI *Student Model* "Direction of Motion"



Title:	FCI-ish student model
Summary	Propensities to respond to tasks in a certain class (e.g., FCI and FMCE items) in terms of conception models. The conceptions are Newtonian, Galilean, and nonscientific. The model is identified by implicitly fixing all examinees at zero, so there are only two SM variables, namely for the Galilean and nonscientific propensities.
Distribution Summary	Bivariate normal for the two SM variables that are explicit
Distribution Type	Multivariate normal
Covariance Matrix	[View] 1 0 0 1
Means Matrix	[View]
Student Model Variables	Galilean propensity. nonscientific propensity.
I am a kind of	
These are kinds of me	
These are parts of me	
Online resources	
References	
I am a part of	Force Problems--Gravity Only. (Template) Force Problems--Horizontal Only. (Template)

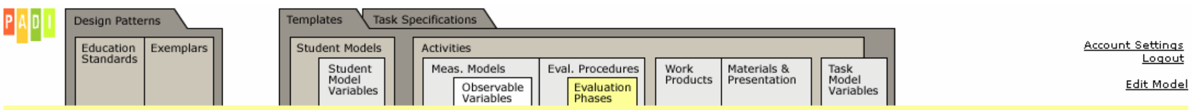
Figure A-6: PADI *Evaluation Procedure* "Map Multiple-Choice Answers onto Conceptual Model"



Map multiple-choice answers onto conceptual model | Evaluation Procedure (rubric) 290 [View Tree | Export]

Title:	Map multiple-choice answers onto conceptual model
Summary	e.g., FCI answers mapped onto Newtonian, Aristotelian, and nonscientific models.
Evaluation Phases	Model using multiple choice. Multiple-choice evaluation option for task templates developed under model-using design pattern such...
Online resources	
References	
I am a part of	Make explanations and predictions from a physical situation. (Activity)

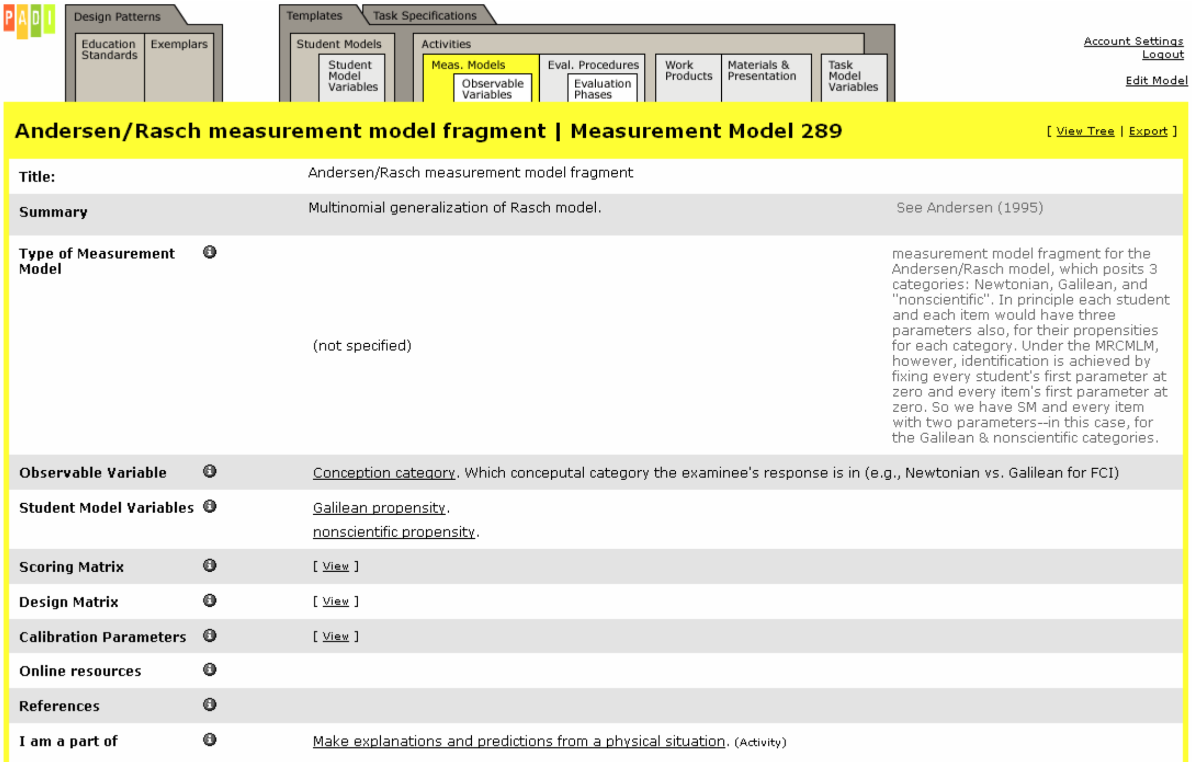
Figure A-7: PADI *Evaluation Phase* "Model Using Multiple Choice"



Model using multiple choice | Evaluation Phase 327 [View Tree | Export]

Title:	Model using multiple choice	
Summary	Multiple-choice evaluation option for task templates developed under model-using design pattern such as FCI-like or TAP-like assessments.	Note that an evaluation phase entitled "model using open-ended" has also been created, but is not yet linked to an activity or template.
Preceding Evaluation Phase		
Work Products	Choice from proffered choices. The student is to make a selection from among presented choices Right/wrong multiple choice items a... Choice of a Multiple Choice Answer. The task requires students to read a question and choose the best answer.	
Input Observable Variables		
Task Model Variables		
Output Observable Variables	Conception category. Which conceptual category the examinee's response is in (e.g., Newtonian vs. Galilean for FCI)	
Evaluation Action Data	Use a list of known scientific conceptions and misconceptions from prior research (e.g., Tables I & II from Hestenes et al., 1992) to develop the coding key	
Evaluation Action		
Online resources		
References		
I am a part of	Map multiple-choice answers onto conceptual model. (Evaluation Procedure (rubric))	

Figure A-8: PADI *Measurement Model* "Andersen/Rasch Measurement Model Fragment"



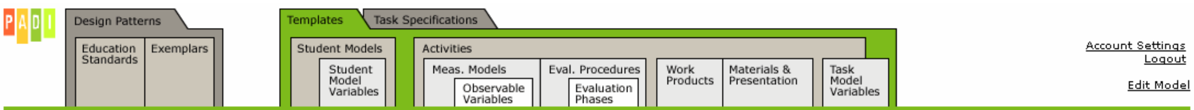
APPENDIX B

PADI Template for Force Problems—Horizontal Only

Appendix B

The PADI *template* for "Force Problems—Horizontal Only" has links similar to those of the *template* for "Force Problems—Gravity Only," but has its own Template-level Task Model Variables. Only the top layer of this *template* is shown.

Figure B-1: PADI *Template* "Force Problems—Horizontal Only"



Force Problems--Horizontal Only | Template 276 [View Tree | Convert to Task Spec | Export]

Title:	Force Problems--Horizontal Only	
Summary	This template is for multiple-choice conceptual Newtonian force problems that do not involve gravity or circular motion.	This template can produce a measure like a subset of Newtonian force problems from the Force Concept Inventory (FCI).
Type	[View]	
Student Model Summary	Student is seen as being in several belief states simultanously (e.g., Newtonian, Galilean, and nonscientific), each with a certain propensity.	In some ways analogous to the Siegler (1976) balance beam study.
Student Models	FCI-ish student model. Propensities to respond to tasks in a certain class (e.g., FCI and FMCE items) in terms of conceptio...	
Measurement Model Summary	Measurement model is multivariate, a la Andersen/Rasch model. Original measurement model was univariate.	Measurement model is an Andersen/Rasch model (Andersen, 1995) being tested by Kevin Huang at UMCP. It can be written as a special case of the MRCMLM (Adams, Wilson, & Wang, 1997). Previous models include Bao and Redish (2001) or simple summary scores.
Evaluation Procedures Summary	Answer key--one correct answer per question.	Correct answer always corresponds to the result of reasoning from a Newtonian conception. (In principle, could have open-ended answers, which would be mapped into model categories--e.g., Minstrell, 1989)
Work Product Summary	Answers to multiple-choice problems are main work product.	Multiple choice responses have been constructed so that each one a priori maps to exactly one of the model classifications. Correct answers apply Newtonian principles correctly to the problem. Incorrect answers reflect non-Newtonian principles; specifically, misconceptions identified in prior literature, which might be Galilean, Aristotelian, or nonscientific. The list of Newtonian concepts tested in the FCI is listed in Hestenes, Wells & Swackhamer (1992), Table I. The list of common misconceptions used to construct distractors is listed in Table II of the same paper.
Task Model Variable Summary	Task model variables include identity, direction, amount, and duration of force applied; mass and identity of object; speed and direction of object; time period of interest (before, during, or after force is applied).	e.g., FCI Q25 amount of force = "constant horizontal force" mass = "large box" speed after force is applied = "Vo" Friction always = 0 and Motion is always in a horizontal plane in this subset of problems, therefore gravity is never a force. Other variables are implicitly or explicitly set constant (e.g., direction not specified, duration not specified, speed of object before force = 0, time period of interest = while the force is applied, path of motion must be a straight line).

(continued)

Figure B-1: PADI *Template* "Force Problems—Horizontal Only" (*continued*)

Template-level Task Model Variables	ⓘ	Amount of force applied. Amount of force which one object exerts on another (moving or stationary) object. Direction of force applied. The direction in which a force is applied to an object Direction of motion. The path taken by an object in motion e.g., Answer choices refer to the path of motion of an ob... Duration. e.g., in FCI-type problem, is a force applied instantaneously or over a period of time. Friction. Amount of friction between two objects such as a puck and ice, a rope and a pulley, a ball and air. Identity of horizontal force. The identity/ies of a force(s) which act(s) on an object(s) for an instant or over a period of time,... Illustrations. Whether or not an illustration (e.g., line drawing, photograph, video clip) is part of the task. Mass. e.g., Mass of object to which force is applied. Objects. Objects on which forces act. They may vary in size, mass, animate/inanimate, etc. Shape of path of motion. The shape of the path taken by an object in motion e.g., Answer choices refer to the path of mo... Speed. e.g. The speed of an object at the moment when a force is applied to it. Time period of interest. Past, present, or future. e.g., Question asks about motion or speed while a force is applied vs. af...	
Task Model Variable Settings	ⓘ	[View]	
Materials and Presentation Requirements	ⓘ	Paper-and-pencil measure.	Could easily be adapted for computer administration.
Template-level Materials and Presentation	ⓘ		
Materials and Presentation Settings	ⓘ	[View]	
Activities Summary	ⓘ	Sets of questions relating to a single situation may be presented or answered in any order. Ordinarily all questions on the FCI are administered at one sitting (it is commonly used as a pretest-posttest measure in university introductory physics courses).	
Activities	ⓘ	Make explanations and predictions from a physical situation. Given a physical situation with some underlying regularities (e.g., a Newtonian law or gas law), stu...	
Tools for Examinee	ⓘ	Pen or pencil.	
Exemplars	ⓘ	Force Concept Inventory (FCI). A multiple-choice measure of students' conceptual knowledge of forces, including Newton's 1st-3rd la...	
Educational Standards	ⓘ		
Design Patterns	ⓘ	Model Using. This design pattern generates tasks where the student has to reason through a given model using data...	
I am a kind of	ⓘ		
These are kinds of me	ⓘ		
These are parts of me	ⓘ		
Online resources	ⓘ	FCI available at http://modeling.la.asu...	
References	ⓘ	Bao, L., & Redish, E.F. (2001). Model analysis: Assessing the dynamics of student learning. Wang (2003)	Available on the World Wide Web at http://www.physics.ohi...
I am a part of	ⓘ		

APPENDIX C

PADI Template for Force Problems—Horizontal and Gravity

Appendix C

The PADI *template* for "Force Problems—Horizontal and Gravity" has links similar to those of the FCI *templates* above, but its own Template-level Task Model Variables. Only the top layer of this *template* is shown.

Figure C-1: PADI *Template* "Force Problems—Horizontal and Gravity"

Design Patterns | Education Standards | Exemplars | Templates | Task Specifications | Student Models | Student Model Variables | Activities | Meas. Models | Observable Variables | Eval. Procedures | Evaluation Phases | Work Products | Materials & Presentation | Task Model Variables

Account Settings
Logout
Edit Model

Force Problems--Horizontal and Gravity | Template 322 [View Tree | Convert to Task Spec | Export]

Title:	Force Problems--Horizontal and Gravity	
Summary	This template is for multiple-choice conceptual Newtonian force problems that simultaneously involve horizontal motion and the downward pull of gravity, but not circular motion.	This template can produce a measure like a subset of Newtonian force problems from the Force Concept Inventory (FCI). Force Problems--Horizontal Only and Force Problems--Gravity Only are special cases of this template.
Type	[View]	
Student Model Summary	Student is seen as being in several belief states simultanously (e.g., Newtonian, Galilean, and nonscientific), each with a certain propensity.	In some ways analogous to the Siegler (1976) balance beam study.
Student Models		
Measurement Model Summary	Measurement model is multivariate, a la Andersen/Rasch model. Original measurement model was univariate.	Measurement model is an Andersen/Rasch model (Andersen, 1995) being tested by Kevin Huang at UMCP. It can be written as a special case of the MRCMLM (Adams, Wilson, & Wang, 1997). Previous models include Bao and Redish (2001) or simple summary scores.
Evaluation Procedures Summary	Answer key--one correct answer per question.	Correct answer always corresponds to the result of reasoning from a Newtonian conception. (In principle, could have open-ended answers, which would be mapped into model categories--e.g., Minstrell, 1989)
Work Product Summary	Answers to multiple-choice problems are main work product.	Multiple choice responses have been constructed so that each one a priori maps to exactly one of the model classifications. Correct answers apply Newtonian principles correctly to the problem. Incorrect answers reflect non-Newtonian principles; specifically, misconceptions identified in prior literature, which might be Galilean, Aristotelian, or nonscientific. The list of Newtonian concepts tested in the FCI is listed in Hestenes, Wells & Swackhamer (1992), Table I. The list of common misconceptions used to construct distractors is listed in Table II of the same paper.
Task Model Variable Summary	Task model variables include identity, direction, and amount of force applied; released from moving or still object; mass, size, and identity of object; horizontal distance traveled; path of motion.	e.g., FCI Q12 identity of force = cannon blast and gravity simultaneously direction of force = horizontal and downward simultaneously amount of force = cannon blast and g = 32 ft/sec^2 released from moving or still object = still mass = implied heavy size = implied medium sized identity = cannonball path of motion = TBD (parabola) Irrelevant: horizontal distance traveled

(continued)

Figure C-1: PADI *Template* "Force Problems—Horizontal and Gravity" *(continued)*

Template-level Task Model Variables	Amount of force applied. Amount of force which one object exerts on another (moving or stationary) object. Direction of force applied. The direction in which a force is applied to an object Direction of motion. The path taken by an object in motion e.g., Answer choices refer to the path of motion of an ob... Friction. Amount of friction between two objects such as a puck and ice, a rope and a pulley, a ball and air. Identity of horizontal force. The identity/ies of a force(s) which act(s) on an object(s) for an instant or over a period of time,... Illustrations. Whether or not an illustration (e.g., line drawing, photograph, video clip) is part of the task. Mass. e.g., Mass of object to which force is applied. Objects. Objects on which forces act. They may vary in size, mass, animate/inanimate, etc. Shape of path of motion. The shape of the path taken by an object in motion e.g., Answer choices refer to the path of mo...	
Task Model Variable Settings	[View]	
Materials and Presentation Requirements	Paper-and-pencil measure.	Could easily be adapted for computer administration.
Template-level Materials and Presentation		
Materials and Presentation Settings	[View]	
Activities Summary		
Activities	Make explanations and predictions from a physical situation. Given a physical situation with some underlying regularities (e.g., a Newtonian law or gas law), stu...	
Tools for Examinee	Pen or pencil.	
Exemplars	Force Concept Inventory (FCI). A multiple-choice measure of students' conceptual knowledge of forces, including Newton's 1st-3rd la...	
Educational Standards		
Design Patterns	Model Using. This design pattern generates tasks where the student has to reason through a given model using data...	
I am a kind of		
These are kinds of me		
These are parts of me		
Online resources	FCI available at http://modeling.la.asu...	
References	Bao, L., & Redish, E.F. (2001). Model analysis: Assessing the dynamics of student learning. Wang (2003)	Available on the World Wide Web at http://www.physics.ohi...
I am a part of		

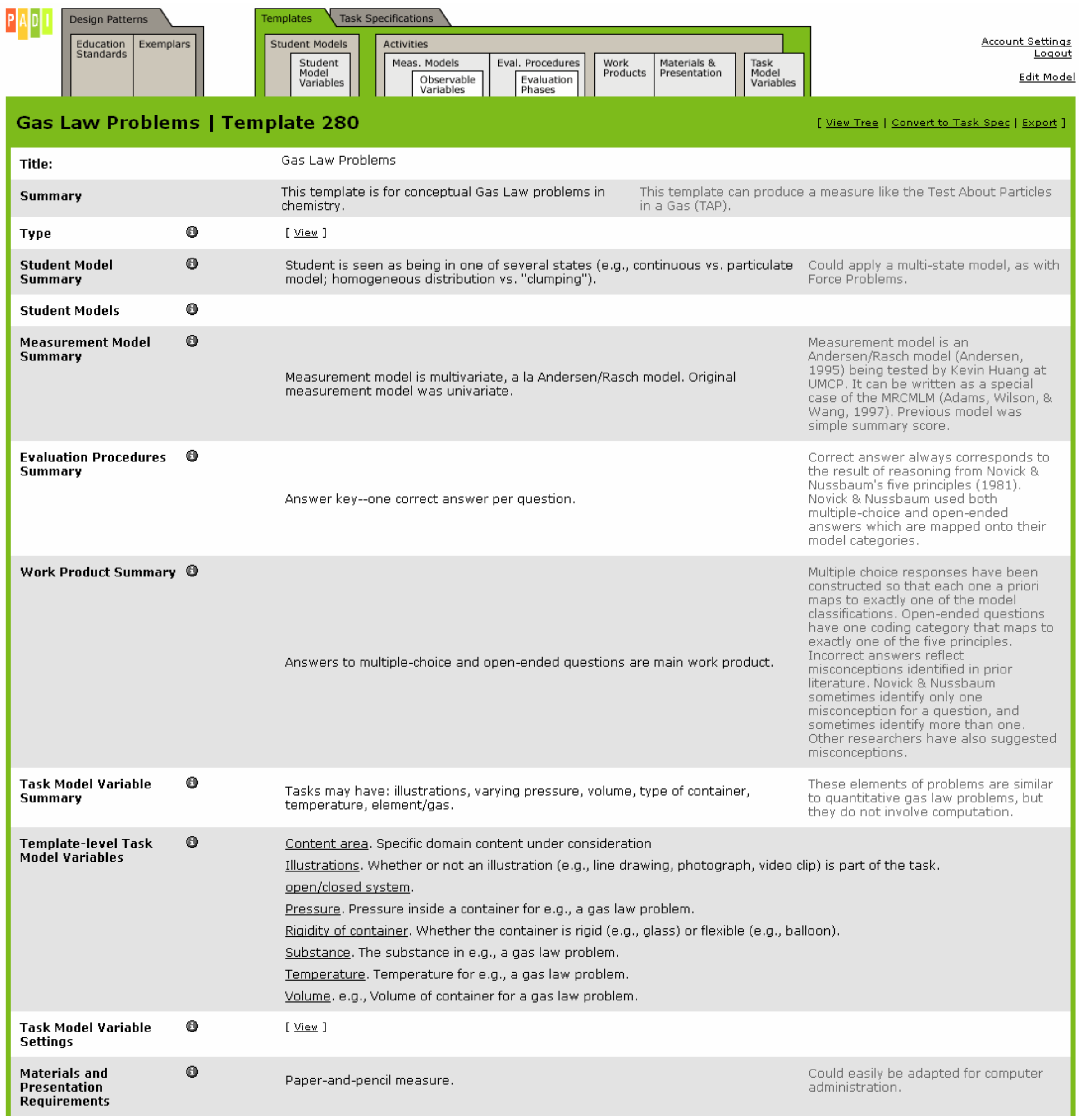
APPENDIX D

PADI Template for Gas Law Problems

Appendix D

The PADI *template* for “Gas Law Problems” reproduced below has its own specific information about the Student Model, the Measurement Model (e.g., mapping student-constructed responses to predetermined misconception categories), and Task Model (e.g., for constructing both multiple-choice and constructed-response items), as well as references to the TAP measure and other print resources. The same Activity used to structure the FCI force tasks (displayed in Appendix A) is reused in this *template*. Only the top layer of the *template* is shown.

Figure D-1: PADI *Template* “Gas Law Problems”



Title:	Gas Law Problems	
Summary	This template is for conceptual Gas Law problems in chemistry.	This template can produce a measure like the Test About Particles in a Gas (TAP).
Type	[View]	
Student Model Summary	Student is seen as being in one of several states (e.g., continuous vs. particulate model; homogeneous distribution vs. "clumping").	Could apply a multi-state model, as with Force Problems.
Student Models		
Measurement Model Summary	Measurement model is multivariate, a la Andersen/Rasch model. Original measurement model was univariate.	Measurement model is an Andersen/Rasch model (Andersen, 1995) being tested by Kevin Huang at UMCP. It can be written as a special case of the MRCMLM (Adams, Wilson, & Wang, 1997). Previous model was simple summary score.
Evaluation Procedures Summary	Answer key--one correct answer per question.	Correct answer always corresponds to the result of reasoning from Novick & Nussbaum's five principles (1981). Novick & Nussbaum used both multiple-choice and open-ended answers which are mapped onto their model categories.
Work Product Summary	Answers to multiple-choice and open-ended questions are main work product.	Multiple choice responses have been constructed so that each one a priori maps to exactly one of the model classifications. Open-ended questions have one coding category that maps to exactly one of the five principles. Incorrect answers reflect misconceptions identified in prior literature. Novick & Nussbaum sometimes identify only one misconception for a question, and sometimes identify more than one. Other researchers have also suggested misconceptions.
Task Model Variable Summary	Tasks may have: illustrations, varying pressure, volume, type of container, temperature, element/gas.	These elements of problems are similar to quantitative gas law problems, but they do not involve computation.
Template-level Task Model Variables	Content area. Specific domain content under consideration Illustrations. Whether or not an illustration (e.g., line drawing, photograph, video clip) is part of the task. open/closed system. Pressure. Pressure inside a container for e.g., a gas law problem. Rigidity of container. Whether the container is rigid (e.g., glass) or flexible (e.g., balloon). Substance. The substance in e.g., a gas law problem. Temperature. Temperature for e.g., a gas law problem. Volume. e.g., Volume of container for a gas law problem.	
Task Model Variable Settings	[View]	
Materials and Presentation Requirements	Paper-and-pencil measure.	Could easily be adapted for computer administration.

(continued)

Figure D-1: PADI *Template* "Gas Law Problems" *(continued)*

Template-level Materials and Presentation	ⓘ	
Materials and Presentation Settings	ⓘ	[View]
Activities Summary	ⓘ	Questions may be presented or answered in any order. Ordinarily all questions on the TAG are administered at one sitting.
Activities	ⓘ	Make explanations and predictions from a physical situation. Given a physical situation with some underlying regularities (e.g., a Newtonian law or gas law), stu...
Tools for Examinee	ⓘ	Pen or pencil.
Exemplars	ⓘ	Test About Particles in a Gas (TAP). This is a paper-and-pencil measure of students' conceptual understanding of gases. It includes both ...
Educational Standards	ⓘ	
Design Patterns	ⓘ	Model Using. This design pattern generates tasks where the student has to reason through a given model using data...
I am a kind of	ⓘ	
These are kinds of me	ⓘ	
These are parts of me	ⓘ	
Online resources	ⓘ	
References	ⓘ	Novick, S., & Nussbaum, J. (1981). Pupils' understanding of the particulate nature of matter: A cross-age study. Science Education, 65(2), 187-196.
I am a part of	ⓘ	

APPENDIX E

PADI Design Pattern for Model Using

Appendix E

The PADI "Model Using" *design pattern* is reproduced below. It includes a Summary, KSAs (knowledge, skills, and abilities), Potential Observations, Potential Work Products, and Characteristic and Variable Features of the *design pattern*. The KSAs include both Focal KSAs (e.g., the importance of conditional knowledge) and Additional KSAs (e.g., general knowledge). Potential Observations and Work Products are very high-level statements that are operationalized in the *templates* as Student Model and Task Model Variables (e.g., Work Products in the Activity). Characteristic and Variable Features are likewise abstract statements that are operationalized in the *templates* as Task Model Variables.

Figure E-1: PADI *Design Pattern* "Model Using"

PADI | Design Patterns: Education Standards, Exemplars | Templates | Task Specifications: Student Models (Student Model Variables), Activities (Meas. Models, Observable Variables, Eval. Procedures, Evaluation Phases, Work Products, Materials & Presentation, Task Model Variables)

Account Settings
Logout
Edit Model

Model Using | Design Pattern 274 [View Tree | Export]

Title:	Model Using	
Summary	This design pattern generates tasks where the student has to reason through a given model using data that do not contradict the model.	One type of problem solving that involves learning is the application of a known model to data that do not contradict the model. Students' work is bound by the concept of a known model (or models), so their work includes an understanding of the constraints of the problem.
Focal Knowledge, Skills, and Abilities	Being able to reason through the concepts and relationships of a given model. Conditional knowledge: knowing when to apply the model.	Models may be correct (conventional scientific) or not (e.g., misconceptions or limited cases [p-prims, facets]), but students do learn how to apply them to problems, and in the process consolidate their understanding of the model.
Rationale	The activities motivated by this pattern have students reasoning through a model, to make explanations, predictions, and inferences such as filling in missing information.	
Additional Knowledge, Skills, and Abilities	Familiarity with task type (e.g., materials, protocols, expectations). Subject-area knowledge (declarative and procedural).	
Potential observations	Given a model and a situation, making explanations, predictions, or retrodictions reasoned through the model. Making and explaining predictions through a model.	This DP is characterized by the absence of model modification--that is another design pattern. In model-using, the model is unproblematic to the student.
Potential work products	Correspondence mapping between elements or relationships of model and real-world situation. Correspondence mapping between elements or relationships of overlapping models. Hypotheses (constructed/selected). Predictions (constructed/selected). Written/Oral Explanation of reasoning.	
Potential rubrics		
Characteristic features	Real-world situation and one or more models appropriate to the situation, for which details of correspondence need to be fleshed out. Focus is on reasoning about the situation, through the schema and relationships embedded in the model. Addresses correspondence between situation and models, and models with one another. Patterns in the data do not contradict the model.	
Variable features	Is problem context familiar? Must experimental work or supporting research be carried out in order to ground the elaboration? Single model to reason through, vs. establishing correspondence among and reasoning through models at different levels or with different focus?	
I am a kind of	Scientific Reasoning. This design pattern concerns a scientific problem to solve or investigate. Do they effectively plan ...	
These are kinds of me	Interpretation of Dynamic Graphs. Students are provided with a model in which they can manipulate model parameters and view the result...	
These are parts of me		
Educational standards		

(continued)

Figure E-1: PADI "Model Using" ***(continued)***

Templates	ⓘ	
Exemplar tasks	ⓘ	Force Concept Inventory (FCI). A multiple-choice measure of students' conceptual knowledge of forces, including Newton's 1st-3rd la...
Online resources	ⓘ	
References	ⓘ	diSessa, A. A. (1993). Toward an epistemology of physics. Cognition and Instruction, 10(2 & 3), 105-225. Hunt, E., & Minstrell, J. (1994). A cognitive approach to the teaching of physics. In K. McGilly (Ed.), Classroom lessons: Integrating cognitive theory and classroom practice (pp. 51-74). Cambridge, MA: MIT Press. NSES standards. Stewart, J., & Hafner, R. (1994). Research on Problem Solving: Genetics. In D. Gabel (Ed.), Handbook of Research on Science Teaching and Learning (pp 284-300). New York: MacMillan. White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. Cognition and Instruction, 16(1), 3-118.
I am a part of	ⓘ	

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