

## **Roles for Explanatory Models and Analogies in Conceptual Change**

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### ***Models, Conceptual Change, and Initial Teaching Strategies***

In this chapter I will review some major approaches to instruction for producing conceptual change in scientific explanatory models, including the use of analogies. While space prevents a full review here, I want to present enough research to describe some of the interesting interrelationships between analogies, models, and conceptual change. I will put more emphasis on literature from science education, since Jonassen (this volume) has emphasized findings on models from educational psychology. I will concentrate on model based, cognitive strategies for fostering conceptual change in science as an outcome in individual students. Many of these strategies will involve considering the roles that group discussions and co-construction with a teacher can play, and so some socio-cognitive processes will be included. To be sure there are other recent studies that address other social, cultural, metacognitive, and motivational factors that can have very important influences on conceptual change. However, we still need to address an enormous gap that remains at the core of conceptual change theory: we do not have an adequate cognitive model of the basic conceptual change process. Most of the “classical theory” of conceptual change in science education (Posner, et al., 1982, Strike and Posner, 1992) is either about *conditions* for change (e.g. dissonance), *effects* of change (e.g. a more plausible conception, developmental stages of conceptions), or *factors* that make it easier or more difficult (e.g. the presence of a persistent misconception). What is missing is a fuller specification of *mechanisms* of conceptual change. Many suspect that models and analogies can play a central role in conceptual change. But there is not even a consensus on a definition for the term model itself. And we are hard pressed to describe something as basic as the relationship between analogies and models in science learning. Historians of science such as Hesse (1966) and Harre (1972) understood that this relationship is complex and subtle in science itself, so we should expect no less in the area of student learning. Thus, there is still much work to do within the basic cognitive core of individual conceptual change theory as well as outside that core in motivational, metacognitive, and socio-cultural realms.

### **Conceptual Change and Mental Models**

The term *conceptual change* has been used in a variety of ways. Thagard (1992) describes a spectrum of possible degrees of change, from changes in relatively surface-level details, or small revisions, to radical shifts in core concepts. A definition of conceptual change that fits well with Thagard’s spectrum is learning in cases where a new knowledge structure is developed--a change that is structural or relational in character rather than a change in surface features. This could occur via the construction of a new structure or a modification or replacement of an old structure. Later in the chapter I will also advocate broadening this definition slightly to include cases where the domain of application of a structure changes significantly. I also choose to use a rather broad concept of 'knowledge structure' to allow for the possibility of perceptual and motor structures as part of what is

changed.

Developing a stable vocabulary with which to talk about *models* is one of the major challenges in this area. In its widest use in the literature, the term *mental model* is almost too large a category to be useful, essentially meaning any knowledge structure that represents a number of relationships between interconnected entities in a system, as opposed to a list of isolated facts. This allows a model to account for many events, making it an efficient kind of knowledge representation. Gilbert et al. (1998) point out that models focus the user on certain features in a system. Here I will use the term mental model in the broad sense to mean a (mental) representation of a system that focuses the user on certain features in the system and that can predict or account for its structure or behavior (Clement, 1989). I will make some minimal assumptions about useful mental models. Useful mental models are often idealized; one might say they are always simplified, since we cannot comprehend every microscopic detail of entities in the world. This corresponds more or less to Nancy Nersessian's (this volume) definition of mental model: "A mental model is a conceptual system representing the physical system that is being reasoned about. It is an abstraction--idealized and schematic in nature--that represents a physical situation by having surrogate objects and properties, relations, behaviors, or functions of these that are in correspondence with it." I want to be careful, however, to take "abstraction" here to mean something with a degree of generality—as opposed to something completely non-concrete or non-imagistic—because I want to include the possibility of schematic, imagistic mental models that are concrete in the sense of being perception-like, but that are abstract in the sense of being schematic and general. For example, different people can have mental models at different levels of depth for, say, an old style 3-speed bicycle. Some people may include a schematic image of a moving chain, bearings, and cables for brakes, internal gear shift mechanism, and gyroscopic action of the wheels, but other individuals are missing some or all of these elements (Piaget, 1930). Such a mental model is abstract in the sense of being simplified, schematic, and somewhat general, in that it applies to millions of bikes, but it may be concretely imageable. *External models*, such as diagrams, may serve to record features of a mental model, and may allow one to develop a model too complex to be stored or envisioned at once in working memory.

**Scientific models.** Minimal criteria for considering a mental model to be a *scientific model* include the requirement for a certain level of precision; the requirement for a basic level of plausibility that rules out, for example, occult properties; and a requirement that, if possible, the model be internally consistent (not self-contradictory). Under this broad definition, analogies, such as thinking about water wave reflection for light reflection, or a mechanical thermostat for the body's temperature regulation system, can also be scientific models when they are used in an attempt to predict or account for the behavior or structure of the system.

### **Explanatory vs. Non-Explanatory Models**

Harrison and Treagust (1996) discuss a pantheon of types of models, including the scale model, analogical model, mathematical model, chemical formula, theoretical model, a standard (something to be imitated), maps and diagrams. To complement this pantheon I have found it helpful to make two orthogonal distinctions to help focus this chapter on a narrower "space" of models. Along one dimension lies the familiar distinction between

quantitative and qualitative models-I will focus on the latter. The other dimension requires more introduction. Historians of science, such as Campbell (1920), Hesse (1966), and Harre(1972 ), have developed important distinctions between empirical law hypotheses, explanatory models, and formal principles; these form the vertical dimension depicted in Table 1. These historians believe that hypothesized, theoretical, qualitative models (I will call these ‘*explanatory models*’), such as molecules, waves, and fields, are a kind of hypothesis separate from empirical patterns or observational descriptions of behavior. Campbell gives the example that merely being able to make predictions from the empirical gas law stating that PV is proportional to RT is not an explanatory model-it is not the same as understanding *why* the system behaves as it does in terms of an explanatory model of molecules in motion. In contrast, the explanatory elastic particle model provides a description of a hidden, non-observable mechanism that explains *how* the gas works and answers *why* questions about the causes underlying observable changes in temperature and pressure. As a special kind of scientific model, an explanatory model is not simply a condensed summary of empirical observations, but is rather a set of new theoretical terms and images that are part of the scientist's view of the world. Following Peirce, Harre and Hesse believe that an explanatory model is neither "given" in, nor implied by, the data. Rather it is an invention that is conjectured and then retained if it successfully explains the data. The precision of such a model can be extended by adding a mathematical description of relations between variables in the model. These distinctions helped Clement (1989) explain how experts thinking aloud could develop successful predictive knowledge at the Empirical Law Level in Table 1, yet be unsatisfied that they *understood* a system at the Explanatory Model Level.

Beyond these basic features, scientists often prefer explanatory models that are general, visualizable, simple, and that contain familiar entities (Nagle, 1961). More extensive sets of evaluatory criteria for a “good” explanatory model are discussed by Kuhn (1977) and Darden (1991). Level 4 in Table 1 contains *formal theoretical principles*, such as the Laws of Thermodynamics or Newton’s laws, that consolidate general features of the mechanisms from the Explanatory Model Level and state them as part of a formal deductive system. For a discussion of studies of other kinds of models, such as graphs, charts, and maps (e.g. Lehrer and Schauble, 2003; Raghavan and Glaser, 1995) familiarity with which may be an important prerequisite for preparing young children to work with explanatory models, see Jonassen (this volume).

Why focus on explanatory models? Authors such as Machamer and Darden (2000), Campbell (1920), Harre (1972), Nagel (1961), and Hesse (1966) have argued that qualitative explanatory models (mechanisms) are at the central core of most theories, and that to develop successful explanatory models is a central goal of most sciences. Such a model is seen as the means by which a theory takes on meaning, and, if used flexibly, it gives the theory the power to explain and make predictions for new cases that the subject has not seen. On this account, significant changes that improve an explanatory model are one of the most important, if not the most important type of conceptual change (Lawson, et al., 2000, National Research Council, 2011; Perkins & Grotzer, 2005; Windschitl, et al., 2008).

### **The Strategy of Presenting Models**

Perhaps the most direct approach is that of *presenting* descriptions of models in a concise

and clear way. For example, studies by Mayer (1989) have done this via schematic diagrams and text, finding, in many cases, that for presented explanations of mechanical systems (e.g. how car brakes work), the inclusion of a clear and simple diagram can yield a significant improvement in conceptual understanding (but usually not in factual knowledge), especially for students who have low spatial ability. Work by Hegarty, et al. (2003) indicates that learners can be induced to mentally animate static diagrams of dynamic processes. In a related vein, Gabel (1999) found that adding the use of physical block models of molecules to chemistry lessons increased middle school students' comprehension of chemistry reactions and principles. Such studies indicate that a focus on communicating the visual aspects of explanatory models can make a positive difference in instruction.

Other studies, however, have revealed limitations of presentation approaches. Lowe (1993) found that the mental representations derived by experts and novices from abstract technical diagrams (weather maps), depended on their ability to process the material in terms of dynamic relations between the components of the diagrams. Those who lacked prerequisite concepts did not comprehend the presented diagrams. A set of "disaster studies" in physics in the early eighties, too numerous to review here, provided evidence that lecture presentations had not adequately deal with the problem of persistent misconceptions, and similar results have been produced to some extent in biology and chemistry. Even though college physics students, including engineering majors, were often able to learn to solve quantitative problems using algebraic formulas, they had great difficulty with many qualitative conceptual problems. This suggests that superficial knowledge at Level 4: Formal Theoretical Principles, in Table 1, does not imply understanding at Level 3: Explanatory Models, and it highlights the sometimes unrecognized importance of Level 3 in science education.

## ***Dissonance Producing Approaches***

### **Dissonance Strategies**

Teaching by direct contrast. Although I have chosen to define the concept of conceptual change more broadly, the problem of producing change in persistent misconceptions is especially interesting and challenging. In this chapter I will use the terms: *target model* or *target conception* for a scientific conception (or approximation thereof) that is to be learned in a course; *misconception* (also called an *alternative conception*) for a student's conception that is incompatible with a target conception; and *preconception* for a students' conception that is present before instruction in the course. Some misconceptions are perfectly adequate for use in daily life, but others are not, such as those affecting health issues. However, it is important not to show disrespect for students' ideas, in order to encourage their expression and examination. Some misconceptions may be articulated beliefs, others can be implicit intuitions, others can be mental models assembled upon encountering a specific situation.

The most direct attempts to deal with misconceptions have been to refer intentionally to a common misconception during instruction and to contrast it with the scientists' view. Guzetti et al. (1993) reviewed a number of studies of refutational texts—documents in which typical misconceptions are refuted directly in juxtaposition to the

scientific view--and found that, overall, there was evidence of a positive effect. A related but somewhat milder approach is to draw out students' conceptions, relate them to observations, then hold up the target model in comparison. McCloskey (1983) found positive effects from asking high school mechanics students to explain their conceptions of force and motion and then contrasting these with the scientific view. This is called "contrastive teaching" by Schecker and Niedderer (1996), who believe that the student's original conception may not disappear, but that students can become aware of the difference between the two points of view.

Discrepant events. Others have attempted to create more subtle forms of "participative dissonance" less directly, where information is provided that allows the student to discover a conflict with his or her own current model. Discrepant events are empirical experiments, data summaries, or demonstrations that provide data that could promote dissonance with students' preconceptions. Early studies reporting some success in using this technique have appeared in physics (e.g. Stavy and Berkovitz, 1980; Rowell and Dawson, 1985; Arnold and Millar, 1987); chemistry (Hand and Treagust, 1988), and biology (e.g. Dreyfus, Jungwirth, and Elioitch, 1990), and two studies reporting significant differences in gains in favor of experimental groups are Zietsman and Hewson (1986) and Licht (1987).

Theoretically, the simplest mechanism for how dissonance may work is *replacement*. After dissonance with a misconception is produced, the conception is either discarded or suppressed. Another conception then takes its place. Chiu, et al. (2002) reported significantly more "radical conceptual change" in experimental tutoring sessions than in a control group. In transcript analyses, they found evidence that producing cognitive dissonance in students, by having them first explain their own concepts and only then presenting conflicting evidence, appeared to be an important strategy (among others) for fostering understanding and preventing students from memorizing answers by rote. In a study of ninth graders learning about causes of the seasons, Tsai and Chang (2005) found significant gain differences in favor of groups that were encouraged to explain the seasons in their own terms (e.g. summer occurs when the earth is closest to the sun), after which they were presented with discrepant evidence (e.g. the earth is farther in the summer). Again, they interpret this as a way to prevent rote memorization, since the control group's answers were more evenly matched to the experimental group's immediately after instruction, but deteriorated on delayed post tests, as misconceptions 'reemerged'.

Some authors recognize that the purpose of a discrepant event is not just to promote dissonance with existing conceptions, but also to introduce a controversial question into a class in order to promote active discussion. Working from a theory of optimal dissonance for learning motivation, Inagaki and Hatano (1977) showed that student comprehension can be heightened by asking each student to commit to a prediction for an experiment or event to be discussed. This view of the role of dissonance is more complex than a simple conflict theory.

Other dissonance producing strategies. Dissonance can come from a variety of sources in addition to discrepant events. Another source is student-student dissonance, between different students' spontaneous ideas about a predicted phenomenon (Scott, 1992). Other studies using this approach include Dreyfus, Jungwirth, & Elioitch (1990);

Niedderer and Goldberg (1996); Hewson & Hennessey (1992); and Posner, Strike, Hewson, and Gertzog (1982); and Jonassen (this volume).

### **Critiques of Dissonance Strategies**

Other studies however, argue that using discrepant events alone does not always work, for several possible reasons:

- *Lack of effect of single discrepant event:* Chinn and Brewer (1998) have catalogued a variety of student reactions to discrepant information, including cases where they ignore it or do not place it in conflict with their previously stated beliefs (see also Dupin and Johsua, 1989).
- *Affective critique:* In the Dreyfus, et al., study cited above, the authors noted that, while the brighter, more successful students reacted enthusiastically to "cognitive conflicts," the unsuccessful students developed negative attitudes and tried to avoid conflicts. Stavy (1991) suggested avoiding conflict to prevent students' loss of confidence and possible regression.
- *Omission critique:* From a theoretical standpoint, using conflict strategies alone appears not to deal with building up a complex new explanatory model once the old model is called into question. (Chan, Burtis and Bereiter, 1997). After dissonance is created with an initial model, an one always rely on students to simply invent a replacement model?
- *Replacement critique:* Other theoretical objections have been posed by authors such as Smith, diSessa, and Roschelle (1993), who worry that:  
"Instruction designed to confront students' misconceptions head-on ... seems destined to undercut students' confidence in their own sense-making abilities....In focusing only on how student ideas conflict with expert concepts, the misconceptions perspective offers no account of productive ideas that might serve as resources for learning. Since they are fundamentally flawed, misconceptions themselves must be replaced." (p.18).

Instead, they argue for more continuous approaches to teaching that engender developmental continuity. diSessa (1988) and his colleagues, such as Hammer (1996), as well as Clement, et al. (1989), and Minstrell and Krauss (2005), have also advocated an increased focus on students' useful conceptual resources, in contrast to an exclusive focus on misconceptions.

Summary. In summary, a positive characteristic of the studies favoring dissonance strategies cited above is that they embodied new recognition of the persistence of some student misconceptions, and corresponding recognition of a need to design instruction in a way that could deal with these misconceptions. Others however, worry that such techniques on their own could be insufficient or even have negative affective consequences for some students. These controversies, despite the positive results of some dissonance studies, indicate the need for further research that investigates the effect of different types or levels of dissonance, and other strategies such as analogies.

### ***Instruction Using Analogies***

Some authors have pointed to the use of analogies as a positive approach to fostering

conceptual change. Johsua and Dupin (1987) found that students studying electricity showed very limited change in the belief that current is “used up” in a bulb in a DC circuit after they were confronted with what the teacher hoped would be a discrepant event: data showing that the current was the same on each side of the bulb. However, when an analogy between electron flow in series circuits and a train running on a circular track was discussed with the students, a significant number changed to a constant-current point of view. Thus, this study pointed both to a limitation of one discrepant event and to the positive effect of an analogy.

### **Theoretical Potential of Analogies**

Analogies are seen by some as an alternative to dissonance (Stavy, 1991) and replacement. Some useful reviews of instructional analogies already exist (Dagher, 1994, 1995; Duit, 1991, Coll, France, & Taylor, 2005), so I will focus here on studies relevant to discussing the relationship between analogies and explanatory models. Theoretically, analogies are said to tap existing knowledge in the learner that is similar enough to a target conception to allow some relational information to be transferred,--to be inferred in the target (Gentner, 1989; Gorsky & Finegold, 1994; Simons, 1984; Stavy, 1991; Stepich & Newby, 1988). Analogies make explicit use of students’ prior knowledge in a positive way. This represents an important shift from focusing on student prior knowledge only as problematic misconceptions. Analogy also holds out hope for efficient global change in bigger steps than a small revision, since one may be able, theoretically, to “import” a whole set of interconnected relations from the base of the analogy to the model.

### **Classroom Learning Trials**

A number of authors have measured learning gains associated with instruction that uses analogies, including Bulgren, et al. (2000), Glynn (1991), Mason (1994), Harrison and Treagust (1996), Treagust and Venville (1996), Dupin and Johsua (1989), Podolefsky & Finkelstein (2007), Minstrell (1982), Brown (1992b, 1994) Brown and Clement (1992), and Clement (1993). Glynn (1991) introduced a six step strategy he called a “Teaching with Analogies (TWA)” approach that includes steps for mapping similarities between the analogue and target explicitly, and indicating where the analogy breaks down. When these steps are taken in interactive discussion, this strategy goes well beyond that of presenting the analogy in lecture.

### **Limitations of Analogies**

Others, however, have sounded caution on some limitations of using analogies, several of which are summarized in Table 2. (Yerrick, et al., 2003; Else et al., 2008). For example, Harrison and Treagust (1996), in a study of the effectiveness of analogies used in 8th to 10th grade classrooms, write: “It appears that many students do not interpret teacher metaphors and analogies in the intended manner. Rather, they transfer attributes from the teachers’ analog to the target . . . in a literal and undifferentiated sense.” (p. 511) Although they found some positive effects of analogies, they found that some students preferred less accurate models of atoms over others and that many students thought that atoms were alive and divide like cells. They believe that these ‘dangerous’ features came from analogical models used in instruction, concluding that their study “has illustrated the

negative outcomes that arise when students are left to draw their own conclusions about analogical models." Duit, et al. (2001, p. ) sounded a similar theme in a study where they examined a set of 9th grade lessons on quantum and catastrophe theory phenomena in which students were encouraged to generate their own analogies. The “discuss the limitations” step in Glynn’s TWA strategy described above, is designed to avoid difficulty 3 in Table 2. However, even when that strategy is heeded, students may still make false inferences from an analogy (Else, et al., 2008).

### **Finding a Good Base**

diSessa (1988), Clement et al. (1989), and Hammer (1996), have called for the systematic study of students’ positive preconceptions, or “anchors,” to address problem 1 in Table 2. Clement, et al, (1989) found that different examples of what appears to experts to be the same physical principle varied strongly with respect to whether students could understand them as examples of the principle. This means that one may have to be quite careful in choosing examples for the base of an analogy, i.e. base examples need to be tested with students. Duit, et al., (2001) confirmed this in the case of certain analogies for quantum effects where the base was poorly understood by certain students. Clement et al. (1989) documented that other examples, however, are interpreted correctly by the vast majority of students and therefore can provide good starting points, or “anchors,” for instruction, concluding that many preconceptions are not misconceptions. On the other hand, in areas where students have insufficiently developed anchoring intuitions about the base, those intuitions may need to be developed by real or simulated experiences. Examples are Arons' (1990) activity of having students push large objects in a low friction environment, McDermott's (1984) use of air hoses to accelerate dry ice pucks, diSessa, Horwitz, and White's use of dynaturtle (White, 1993), and Steinberg's (2004) use of air pressure experiments to develop intuitions to be applied later to analogous electrical circuits.

### **Bridging Strategy**

A strategy called *Bridging analogies*, which uses multiple analogies, has been developed to try to overcome difficulty 2 in Table 2 (Brown and Clement, 1989; Clement, 1993). The strategy is used in about a dozen mechanics lessons in Camp et al. (1994). For example, they built on their tutoring study research and work by Minstrell (1982) to construct a lesson on normal forces. A common misconception in this area is that a table cannot push up on a book. Students say the table is only "in the way," serving as a “barrier” that keeps the book from falling, but do not see it as a force-producing entity. The physicist, on the other hand, views the table as elastic—deforming a tiny amount in response to the force from the book and providing an equal and opposite force upward to keep the book from falling. In the lessons, first, an *anchoring example* of a hand pushing down on a spring was used, which draws out a physical intuition in the student that is largely in agreement with accepted physical theory (most students agreeing that the spring pushes up on the hand). Then, a chain of bridging analogies was used, as shown in Figure 1, to gradually transfer the student's intuition, from the anchoring example to a near case of the book on a foam pad, then to the book on a thin flexible board, and finally to the far case of a book on a table. The teachers taught Socratically during this twenty-five minute section, posing questions about each example. This process exemplifies a type of change emphasized by diSessa (1988), that of changing the domain of application, or applicability



conditions, of the “Springiness” conception to encompass the unintuitive case of tables and other rigid objects. This prompts me to add "or significant change in the domain of application of a structure" to the definition of conceptual change given earlier.

*(Figure 1 about here)*

Brown (1992b) conducted a study in which high school chemistry students who had not had physics were asked to "learn aloud" individually as they worked through a textual presentation of the bridging analogies strategy for the book on the table lesson. Students taught with this method had significantly higher pre-post gains than students in a control group. The control group in this case read a passage of equivalent length from a well-known innovative physics textbook which presented many concrete examples of Newton's Third Law after stating the law. This passage focused on citing many examples rather than on developing bridging analogy relations and models with a few carefully selected examples. It was as if the control text were aiming to have the student induce a very general and abstract principle from a large set of unordered examples. In contrast, the superior performance of the experimental group was used to argue that the transfer of a concrete, dynamic model in a systematic, stepwise manner from the anchor toward the target is more effective.

### **Summary of Approaches using Analogy**

In summary, a number of studies have documented promising gains from analogy-based instruction. However, other studies have exposed various problems that can arise, as shown above in Table 2. Identifying the conditions under which analogies succeed and fail is therefore an important problem for future research. The use of analogies is usually considered to be a strategy that is more constructive than disconfirmatory. A remaining potential general criticism of the use of analogy on its own, in addition to the criticisms in Table 2, is that building up a model using an analogy may do little to counteract a persistent prior misconception. Later on, the prior misconception may reassimilate the target T, causing the student to revert to their previous misconception. This suggests the strategy of combining analogies and dissonance producing situations, discussed in the next section. In the combined strategy, in a reciprocal way, analogies might also provide one answer to the "Omission Critique" of dissonance approaches described in the previous major section on dissonance.

### **Combined Strategy: Using Analogies And Dissonance Together**

Minstrell (1982), and curricula by Camp, et al. (1994) and Steinberg (2004) have taken a position that embraces both the use of dissonance and the use of analogies, as summarized by the concept diagram shown in Figure 2. They were impressed with both a) the depth of the persistence problem for misconceptions in many areas of physics; and b) the importance of building on student's intuitions wherever possible (diSessa 1988; Clement, et al., 1989). This combined strategy works to resolve what I call the Prior Knowledge Paradox: constructivist theory tells us to build on what the student knows, but conceptual change research tells us that a significant part of what the student knows is in conflict with scientist's views. The paradox can be resolved if one recognizes that both kinds of knowledge can coexist in students, and that one can use analogies that tap positive

preconceptions to help students deal with other preconceptions that conflict with target models (misconceptions such as M1 in Figure 2).

*(Figure 2 about here)*

For example, in Camp, et al. (1994) the normal forces lesson included not only bridging analogies discussed earlier but also a discrepant event where a light beam reflected from a mirror flat on the teacher's desk to a wall is deflected downward along the wall when a person stands on the desk. This experiment provides dissonance for students who believe that desks are rigid objects that cannot deform to provide an elastic force. In comparison with control groups, this lesson unit has shown large significant gain differences greater than one standard deviation in size, as measured by pre- and post-tests on problems that deal with students' preconceptions. Some students changed their position toward the scientific view during each major section of the lesson, e.g., after the anchor, bridge, microscopic model presentation, and discrepant event sections, leading the author to hypothesize that each technique was helpful to some subset of students. (Clement, 1993). Large significant gain differences were also realized in three other topic areas in mechanics where lessons combined analogies and discrepant events (Brown and Clement, 1992; Clement, 1993).

### ***Model Evolution Strategies***

#### **Multiple Analogies Foreshadow Model Evolution**

Kuhn's (1970) description of science as going through "revolutions" was challenged by Toulmin (1972) who cited examples of historical change processes that appeared to be a more gradual kind of "evolution". Both ideas have been used as metaphors for conceptual change in students (Novak, 1977). Approaches that build up a model in stages by using successive analogies foreshadow a model evolution approach since they involve gradual improvement of the student's model. Harrison and De Jong (2005) describe the use of multiple analogies in chemistry, and Spiro (1991), and Glynn, and Duit (1995) described the use of multiple analogies to gradually build up a student's conception of biological systems such as muscle fibers or the eye, respectively. Chiu and Lin (2005) found that multiple analogies were significantly more effective than single analogies when they were complementary analogies (that spoke to different aspects of the target); when multiple analogies used were similar to each other, they were no more effective than single analogies. Podolefsky and Finkelstein (2007) found that students who were tutored on electromagnetic waves using two "layered analogies" of string and sound waves plus an abstract graph representation gave significantly more sophisticated explanations than students tutored using either the abstract representation alone, or the analogies alone, indicating the desirability of coupling multiple analogies to mathematical representations.

#### **Model Evolution through Successive Evaluations and Modifications**

This raises the issue of an evolution/revolution debate by posing the question as to whether new explanatory models should be (1) evolved incrementally, by starting from

and modifying the student's own ideas, to foster engagement and ease of modification or (2) introduced all at once in order to display their coherence and superior explanatory power by contrast in a more revolutionary manner. The three contrastive teaching studies cited earlier at the beginning of the section on Dissonance Producing Strategies, can be interpreted as advocating a more revolutionary perspective.

On the other hand, Buckley (2000) traced the work of the most successful student in a class that was given many kinds of information resources and that was told to work without direct instruction on learning how the circulatory system works. She characterized this student as the one who was best able to maintain a partial, initially incomplete and faulty, explanatory model of the system-- a model that became more sophisticated as new elements were incrementally added or eliminated. Not only did the student's partial model act as a central place where she added new information coherently, but new *predictions* she made from her partial model generated questions that motivated her to learn more about circulation. This paper weighs in on the side of an evolutionary approach by documenting the potential for engaging and maintaining student reasoning during learning by starting from mostly familiar concepts in a partial model and pursuing a series of implications and improvements. It is unusual in documenting a very student directed approach that worked well for one student, but not as well for others.

(Figure 3 about here)

Most of the teaching strategies previously described in this chapter are utilized in the diagram in Figure 3, which makes explicit a *model evolution* approach involving successive model evaluations and modifications. Clement and Steinberg (2002) reported on a case study in which they used detailed transcripts from tutoring sessions to acquire fine grained data on a series of substantial changes in a student's model of circuits. The middle row of Figure 3 shows the basic shape of the learning process. They found evidence that a cycle of small incremental steps involving dissonance and then constructive activity (including analogies) aided this student in gradually building a more complex model. For example, students who associate power in only circuits with a battery experience dissonance when they light a bulb (temporarily) by discharging a very large capacitor in a circuit with no battery. An analogy between a discharging capacitor that is releasing charge and a pressurized tire that is releasing air helps to begin building up a model that can explain this and many other phenomena. Thus, the model undergoes a *series of successive refinements*. Only two intermediate models are shown in Figure 3, but in practice there can be many more. Most intermediate student models in a topic area are partly correct and partly faulty. When possible the teacher may try to retain the positive pieces, and to promote conflict with each faulty piece, one step at a time, while recruiting elements from prior knowledge (often via analogy) to help repair that part of the model.

The idea of building up the student's model gradually through revisionary change is also discussed by Driver (1983), Treagust, et al. (1996), Dupin and Johsua (1989), and Minstrell and Krauss (2005). It is implicit in the open discussions of lab results advocated by Wells, et al. (1995), who have developed ways of training physics teachers to postpone evaluation of student ideas in order to facilitate such discussions. Scott (1992) and Niedderer and Goldberg (1996), highlighted the importance of the very closely related idea of a *learning pathway* of intermediate states seen as stepping stones between preconceptions and target conceptions (see review by Niedderer [2001]). They point out that such intermediate states can develop from student ideas that are unanticipated,

requiring teaching or tutoring studies, not just task analysis, to determine good pathways. Niedderer views intermediate knowledge states that appeal to many students as 'attractors'. For curricula resulting from such studies, Clement (2008) distinguishes between a "planned learning pathway" specified ahead of time in a lesson plan and an "implemented learning pathway" that results from the teacher using the plan with real students adaptively. As students introduce unanticipated ideas and details, the implemented pathway is bound to be longer and somewhat different from the planned pathway. Nevertheless, the planned pathway is seen as a valuable source of focus. An extended version of this idea applied in higher level planning to multi-year time spans has been dubbed a "learning progression" in articles such as Smith, et al. (2006) as an important principle for developing teaching standards.

Multiple short cycles needed for complex models. Concerning Figure 3, Clement and Steinberg (2002) write that the small step sizes of the revisions were made possible by the careful choice on the part of the tutor of coordinated "small" analogies and "small" discrepant events. *They theorize* is that this makes it possible for the student to participate in suggesting model revisions that are small enough to make immediate sense, allaying concerns expressed earlier about possible negative effects of too much dissonance. Brown (1992a) and Steinberg (2008) documented large gains over control groups using a curriculum on circuits of this kind, including disproportionately large confidence gains in female students. Others who have focused on the explicit development of a series of intermediate models are Gilbert, et al. (1998), Gobert and Buckley (2000) and Niedderer and Goldberg (1996). In a very different context, White (1993) used a series of more than forty short, computer simulation "hit the target" games to successfully teach, one step at a time, a qualitative appreciation of Newtonian force and motion ideas in a virtual frictionless environment.

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Successive refinement cycles in experts. *The description* in Figure 3 *was also influenced by expert studies. On the basis of expert protocols, Clement (1989)* documented examples of expert model construction occurring via an extended evolutionary *cycle of model generation*, evaluation, and modification, *referred to as a GEM cycle*. Experts engaging in theory formation and assessment cycles using analogies have also been discussed by Holland, Holyoak, Nisbett, and Thagard (1986), and Darden (1991). Nersessian (1992, 2002) documents the cyclical progressive revision process, including dissonance, engaged in by Maxwell during his construction of several visualizable models of the electromagnetic field, just prior to formulating his famous field equations.

A dual role for dissonance in model evolution. In the following I highlight some ways in which dissonance is hypothesized to contribute to evolution.

1. Model evaluation. The fostering of dialectic discussions requires the careful development of a spirit of inquiry in the classroom, where students' ideas are

valued. On the other hand, model evolution techniques do require model evaluation and criticism, suggesting the importance of dissonance strategies. Minstrell (1982) discusses strategies for distancing ownership of ideas away from individual students to make criticism non-threatening. Also, students have been observed using discrepant questions and thought experiments to create dissonance themselves, although this may happen only after students are used to discussing models (Nunez-Oviedo, et al., 2007; Stephens and Clement, 2010, 2012). There is some evidence that students' preconceptions in different areas vary in how persistent they are (Gorsky and Finegold, 1994), ranging from being easily discarded (See Nunez-Oviedo, et al. (2008), Stavy and Berkovitz (1980), Zietsman and Hewson (1986)) to very deep-seated (See Clement, 1982, 1993; Hestenes, et al., 1992). In low persistence cases at least, mild forms of dissonance can be used in conjunction with other positive teaching strategies to produce model evolution. Thus, the use of dissonance to deal with misconceptions need not necessarily be associated with strong, confrontational methods (Ramirez and Clement, 1998).

2. *Positive effects of discrepant events or questions.* Clement and Steinberg (2002) point out that discrepant events can be designed not only to generate dissonance with the students' old model, but also to provide a framework of constraints for guiding construction of the new model, thereby making a positive as well as negative contribution to conceptual change. So in Figure 3, the discrepant event is shown both generating dissonance with M2 and constraining the development of M3. Clement and Rea-Ramirez (1998) called this a "Dual effect" of dissonance. In a study of 9<sup>th</sup> graders learning models of heat transfer, She (2004) found that carefully designed discrepant events or questions did help students detect problems in their existing models and also appeared to provide constraints and motivation for constructing the next step in their evolving model. Nersessian (2002) has described similar constraint-based modeling processes in her analysis of Maxwell's thought experiments, and Clement (2008c) describes such processes in experts thinking aloud. Thus instead of limiting ourselves to the choice between "confrontation" and "no confrontation", vaguely defined, there are a variety of sources of dissonance of different strengths, and this suggests intermediate strategies that should be articulated and tested. Whereas some writers have associated dissonance strategies with a replacement view of conceptual change, here dissonance is associated with model evolution instead.

#### Evidence from curriculum trials for effective model (and concept) evolution.

Other studies have provided evidence that model evaluation and modification cycles can be used effectively in biology (Barker and Carr, 1989); Nunez-Oviedo and Clement, 2008; Hafner and Stewart, 1995), chemistry (Khan et al., 2002), Fretz et al. (2002), heat (Linn et al., 1998), electricity (Steinberg, 2008; Clement and Steinberg, 2002), thermal equilibrium (She, 2004), and mechanics (White, 1989, 1993), (Zietsman and Clement, 1997). At an even more fine-grained level than intermediate *models*, Brown and Clement (1992) describe large gains over controls for mechanics lessons that teach students a set of intermediate *concepts* of inertia, such as "keeps going tendency" and "holdback tendency," before leading the students to modify and combine the concepts into a single

expert concept.

### **Instructional Implications of Model Evolution: Teacher Directed or Student Directed?**

I have said very little about how open to novel student ideas the modeling process should be, because teachers and projects vary tremendously on this dimension. Requesting student participation in the model generation, evaluation, and revision process does open up the conversation and make it more student active and student centered, but teachers and students using such approaches need to become comfortable with the idea of discussing intermediate models that are partially incorrect, prior to students developing a more sophisticated model. A middle position on a Teacher Directed/Student Directed continuum has the teacher fostering *co-construction* by stimulating inferences—as illustrated in Figure 4, the teacher has some input to the construction, but is also striving to stimulate student input (Hammer, 1996; Minstrell and Krauss, 2005). The ratio of student to teacher idea generation that is possible is likely to depend on what cognitive resources are available to students for each given topic and on teaching style (Williams and Clement, 2011). An extended discussion of co-construction strategies is given in Clement and Rea-Ramirez (2008).

For example, getting students to speculate on and generate models of systems like the pulmonary system is not hard, even at the middle school level. But students may generate a variety of ideas for model elements, some of which are at odds with the scientific view (air goes from the mouth to the heart), more or less compatible with the scientific view (air goes into your lungs), and partially correct (lungs are like hollow balloons that expand and contract). Five or fifteen contributions can lead to a large variety of ideas, or what Easley (1990) called ‘conceptual splatter.’ Clement (2008b) describes the challenge this poses: a teacher must decide which idea to deal with first in order to keep students in a “reasoning zone”. There is a need to set an agenda, to decide how to draw on the positive portion of the students’ ideas, and this requires that teachers think on their feet, based on what models the students have generated. Nunez-Oviedo et al. (2007), and Williams and Clement (2011) have tracked how a skilled teacher can guide discussions to produce model evolution in the presence of such multiple difficulties. The skills used pose an additional challenge for teachers and teacher education. Inagaki et al. (1998) suggests that one way to reduce the load on the teacher is to have students vote on a limited number of choices-- those that have been researched ahead of time and shown to have many advocates--but such resources are not so common at present. Electronic response systems (Dufresne, et al., 1996) may facilitate this.

### **Theoretical Implications of Model Evolution**

One can extrapolate to form several theoretical hypotheses from the ideas about model evolution reviewed above: (1) While it is not likely that all science models require an evolutionary approach with many GEM cycles for learning to occur, such strategies may be especially needed whenever target models are complex or multiple misconceptions are present. (2) The intermediate steps used in model evolution are reminiscent of the “bridging analogies” approach discussed earlier. However, the intermediate steps represented in Figure 1 are separate analogous *cases* that are potentially observable (e.g. a book on foam rubber), whereas the intermediate models in Figure 3 are non-observable,

explanatory *models* (e.g. more and more adequate models of what drives currents in circuits). Figure 1 shows a chain of analogical connections whereas Figure 3 shows changes in the model itself via successive modifications. Both processes have intermediate elements, but they play different cognitive roles. (3) In their call for small step model revision starting from students' ideas, model evolution approaches support the idealistic positions of diSessa (1988), Smith et al. (1993) and Clement, et al., (1989) and contrast with a global replacement approach. However, model evolution in small step sizes is also an interesting idea theoretically, because it challenges the distinction between a “substantial conceptual change” (in the extreme, a “revolution”) and a minor revision; a long series of small changes in a model could result, in theory, in a very substantial global change. Schwarz, et al. (2009) add the process of applying, or 'Using a model to explain, and predict phenomena' to GEM cycles and propose a learning progression describing substages in elementary students' development of these processes.

As with most models, the models of piecewise conceptual change in Figures 3 and 4 (and their extensions in Williams and Clement [2011] and Clement [2008a,b]) are simplified ones. They are at a medium grain size, although they are different from and considerably more detailed than a simple conflict and replacement model. One advantage of medium grain size is comprehensibility for discussing instructional strategies with teachers. Finer grained, more systemically complex psychological models of students' conceptions are reviewed in Hammer and Brown (this volume). The additional importance of making connections to form coherent 'networks of ideas' in building a model is suggested by Givry and Tiberghien (2012), interpreted here as a cautionary counter to the idea of purely piecewise learning. Rea-Ramirez and Nunez-Oviedo (2008) provide evidence that evolutionary curricula and assessments that also pay attention to unit integration can be designed to aim for this.

### *Types of Conceptual Change and the Need For Multiple Teaching Strategies*

#### **Types of Conceptual Change in Explanatory Model Development**

Types of conceptual change are listed in the left hand column of Table 3. Dagher (1994) sorted researchers' investigations of conceptual change according to where they fell on Thagard's (1992) spectrum of types of conceptual change. I will attempt to paint a somewhat larger spectrum in an attempt to represent the variety of conceptual change types needed in instruction. In particular:

- A small change in a single feature of a model, as in Thagard's (1992) “adding a weak rule”, can be considered a **Minor Model Revision** and can sometimes be accomplished by students who have had minimal prompting.
- diSessa (1988) and Smith, et al. (1993) provide examples where the content of a conception remains largely the same but the **Domain of Applicability is Changed** or expanded significantly so that it applies to new cases.
- Gentner (1989) and Holyoak and Thagard (1989) speak of an inductive process of

**Abstraction** whereby a general schema can be formed by stripping away differences between two or more analogous exemplars. In a related process, Nersessian (1992) writes of scientists forming abstract models with surface features removed.

- Clement and Steinberg (2002) document examples of **Major Model Modification**, such as the change from a focus on pressure to a focus on pressure *differences* as the cause of flows (representing voltage differences as the cause of current flow in electric circuits).
- Vosniadou and Brewer (1992) document a process of **Synthesis** whereby subjects form a hybrid model that combines a prior model with a newly learned model. This process may be related to what Collins and Gentner (1987) described as “pasting component models together” and what Clement (1994, 2008c) refers to as “compound simulation”.
- Through a process of abduction, receiving a presentation (Mayer, 1989), or both, some authors believe that a new initial model can be learned by a process of **Constructing a Model** from known pieces or by transmission.
- Researchers have documented cases of **Concept Differentiation or Integration** that present major challenges to students, such as the differentiation of heat from temperature (Wiser and Carey, 1983; Smith, et al., 1992) or the integration of acceleration and deceleration into a single concept.
- Some researchers believe it is particularly difficult to replace a conception that has the characteristics of one philosophical/ontological category with a conception that has the characteristics of a different category; e.g., changing the conception of *heating as substance transfer* to one of *heating as energy transfer* (Chi, 1992; Thagard, 1992). They refer to **Branch Jumping or Tree Switching**.

At the top of the table is a process that would occur on a larger time scale than an individual conceptual change, and so in some contexts it might be placed on a different dimension than the others. A paradigm shift, such as the shift from Aristotelian to Newtonian mechanics, involves deep changes in many concepts, and therefore one would not expect it to be possible via a single, or even a few, conceptual changes. Therefore a dotted line is shown between it and the other processes. Students’ naïve views of mechanics are not identical to Aristotle’s, and there is a question of whether the shift from naïve physics to Newtonian physics constitutes a paradigm shift, depending on whether one considers naïve physics to be a paradigm. However there is substantial evidence that it is a huge shift that meets stiff resistance. One may need to warn students that the Newtonian view may not make sense immediately until they have attained a coherent critical mass of new concepts, including velocity, acceleration, force, weight, inertial mass, friction force, relative motion, vector addition of velocities, addition of forces, and net force.



Some have endeavored to draw a cutoff line in various places across Table 3 and to reserve the term *conceptual change* only for processes above the line. I am going to resist that impulse here. All of these types, could be seen as conceptual change in certain cases—that is, as a significant change in conceptual understanding. I therefore concur with the preference for including smaller changes in structure as one type of conceptual change, broadly defined. As Dagher (1994) puts it: "Limiting worthwhile conceptual change to radical conceptual change is similar to limiting worthwhile science to revolutionary science." In addition, it is possible that a series of smaller changes can add up to a large structural change, making the drawing of a sharp boundary line difficult.

Resistance to change. it appears that change of any type in Table 3 could meet with more or less resistance from an existing preconception, depending on the strength of that preconception. Thus, it is possible that what looks like a small change from a philosophical or linguistic point of view (near the bottom of Table 3) is actually a huge change from the student's point of view. For example, the idea that air has a small, but significant, weight would seem to be a small attribute change, yet it is very counterintuitive for most middle school students. Thagard's taxonomy itself did not deal with resistance in this sense. Chiu, et al., (2002) describe how different portions of a chemistry unit varied in difficulty according to the kinds of conceptual change involved, roughly consistent with their type in Table 3.

### **Evaluation Processes**

Using the GEM cycle framework as an organizer, Table 3 represents a dimension of *model modification* or replacement that needs to be complemented by another dimension: processes of *model evaluation*, including processes of model confirmation or disconfirmation, and model competition. Any model resulting from a conceptual change should be evaluated intuitively according to whether it makes sense, but also by more established criteria or experiments (cf. Darden, 1991). Such processes have been documented during instruction by Linn, et al., (1998) and Nunez-Oviedo et al. (2007) among others. There is a school of research (stemming from linguistics) on student argumentation structures for model evaluation processes. These vary from those using more formal schemes derived from Toulmin (1972) for tracking arguments, to less formal schemes (see Duschl and Osborne, 2002). Some view argumentation as the public side of model evaluation, but others view argumentation as fulfilling different types of goals of sensemaking, articulating, and persuading (Berland and Reiser, 2008, Passmore & Svoboda, 2011). Model evaluation is an important process skill that has many natural and intuitive manifestations in students (Pluta, et al., 2011), but that also needs to be refined significantly (Hammer and Elby, 2002; Clement, 2008c). Model competition processes have been documented in science by Kuhn (1970), Giere (1988), and Thagard (1992), in scientists' think alouds by Clement (1989, 2008c), and in instruction by Linn et al. (1998), Tabak et al. (1995), Taber (2001), and Nunez-Oviedo and Clement (2008).

### **Need For Multiple Teaching Strategies**

My own opinion, having worked on two, large, model-based curriculum projects in mechanics and in the biology of respiration, is that *all types of change listed in Table 3 are applicable at times as descriptors of student learning processes*. Many of those types

could be involved in a single unit of instruction. This view contrasts with those in the first three sections of this chapter, which focused on interventions primarily using one predominant strategy. Also, this possible variation in learning processes, from very easy to very difficult within a single unit, means that progress may be quite uneven; as a result, teachers are probably not fully prepared to appreciate the range of difficulty that can be present within a unit.

For example, the “Book on the Table” lesson, discussed earlier, aims at more than one type of conceptual change, i.e. a change in applicability conditions (expansion of the domain of exemplars for the “springiness” p-prim) and the construction of a new hidden explanatory model (molecules with springy bonds). In this lesson, one can also see evidence for several types of teaching strategies, including requests for explanation, use of analogies, use of a discrepant event, and the presentation of an explanatory model. Brown (1994) found in a tutoring study, using a lesson of this kind, that different students picked different strategies when asked what they had learned from the most. This and the recognition that there are many types of conceptual change as represented in Table 3 argues that using multiple teaching strategies is an important technique for reaching students. This is exemplified further in Figure 4, which is a highly condensed representation of two hours of instruction that depicts strategies used in a videotaped teaching session. The teacher was piloting a new curriculum unit on pulmonary respiration with a group of four middle school students. She first asked the students to draw their initial ideas about the structure of the lungs. In the figure, the evolving student model is shown from left to right across the middle. The student contributions are across the top, while teacher statements and labeled teaching strategies are across the bottom. The teacher promoted student-active model construction with teaching strategies such as requests for explanation, discrepant questions, analogies, an animation showing O<sub>2</sub> diffusing to blood cells from alveoli, the teacher giving input on a feature of the model, and the exploration of a physical model (string wrapped around artificial grapes on a vine to represent blood vessels and alveoli). Throughout the process, the teacher encouraged the students to evaluate and modify their own and other students’ models by revising their drawings of the lungs and alveoli. Other teachers have also used discrepant events and analogies, but this lesson unit employs a number of teaching strategies in addition to the use of discrepant events and analogy, expanding the image of conceptual change teaching that was depicted in Figure 3 to one that includes multiple methods for evaluating and modifying students' models. In some places here, the primary generator of ideas was the group of students, and in other places, it was the teacher. Figure 4 provides one image of what model evolution via teacher-student co-construction can look like, with both student and teacher inputs to the developing model, making it a social construction. Note that some evaluation strategies are seen as producing dissonance with the current model, whereas others simply speak to a gap in the model.

Tsai and Chang (2005), in their study of learning the causes of the seasons, designed their lesson around a “conflict map” diagram that shows not only *discrepant* information to be introduced, but also multiple kinds of evidence *supporting* the scientific model of the seasons. When included in a curriculum, such multiple strategy diagrams should help teachers focus on the conceptual goals and major cognitive strategies of the lesson (see also diagrams in Camp, et al. [1994]). Achieving focus is no mean feat when operating within the distractions of a real classroom and the somewhat unpredictable

course of a large group discussion.

Figure 4 is organized primarily around a "Major Model Revision" framework as the major type of conceptual change in Table 3 being pursued at that point in the curriculum. It is interesting that "analogy" does not appear in Table 3 as a type of conceptual change. Rather, it is considered here to be one of many types of teaching strategies at a finer grain size level, a sample of which are shown in the bottom row of Figure 4, which can facilitate the conceptual changes in Table 3.

### **Section Summary**

I have posed the possibility that all of the types of conceptual change in Table 3 could be involved in the learning process when a student is developing the model of any complex system such as the conversion of energy in the human body. Multiple model evaluation strategies can also be important. Recognizing the possibility of model evolution and the variety of teaching strategies that can be involved in its many steps, leads one to appreciate the need for multiple teaching strategies rather than simplistic one- or two-strategy models of teaching.

Comment on process goals. This chapter is focused on methods for achieving content goals of conceptual understanding, but this focus can quickly lead one to needing students to become engaged in scientific thinking that speaks to certain process goals. The instructional activities already described fulfill some process goals already, but approaches that also emphasize process goals for their own sake would need to add additional investigation activities. It is possible that certain deep process goals, such as skills for managing self directed inquiry cycles, are better pursued in separate types of activities from those dealing with persistent misconceptions, as opposed to trying to combine them in the same activity--a question for future research. Also, it stands to reason that specialized teaching strategies are possible for each type of conceptual change. I examine this possibility for the case of analogies in the next section.

## ***Multiple Roles for Analogy in Developing Explanatory Models***

### **An Analogy Can Contribute to Building a Model**

The distinction between analogies, explanatory models, and other types of models has been blurred in much of the literature, but once it is established, it makes possible a further clarification of the different types of special contributions that analogies can make to explanatory model construction. Figures 4 and 5 separate the analogous case from the explanatory model, allowing one to see analogy as participating in the revision of the student's prior model; i.e., seeing analogy as one source of ideas for improving a model rather than as identical to, or the sole source of, a model (Spiro et al., 1991; Clement and Steinberg, 2002). In this section, I will expand on this role as the most important one that analogy can play in conceptual change, and I will compare it with other roles.

One of the possible theoretical reasons for using an organizing analogy, such as air pressure for electric potential in circuits, is that it may be very efficient in producing a large conceptual change "all at once" by importing a whole relational structure from a different domain. I call this the "big bang" or "Eureka" theory of analogy in instruction. In fact though, Clement and Steinberg (2002) found that each implication of the global air

pressure analogy must be explored and examined for each type of circuit element or junction. This means that this model is still constructed in small pieces, as depicted in Figure 3, and each piece involves working through its own particular kind of evaluation (via dissonance) and revision cycles in the face of common difficulties. The global analogy of air pressure and flow, in this case, takes weeks to develop fully; it does not necessarily save time, but it appears to increase depth of understanding significantly (Steinberg, 2008). Not all analogies are this global and complex, but Else, Clement, and Ramirez (2007) and Harrison and Treagust (1993) have emphasized that teachers in other areas can underestimate the time and care needed to develop an analogy properly, especially for younger students. These studies indicate that analogies can be viewed inappropriately, as a “quick fix” for student learning, and that it is better to view them as a strategy for in-depth learning of a more encompassing explanatory model and to use them only when time is allocated for that.

### **Learning From Analogies Via Enrichment Vs. Abstraction**

A widely accepted view considers that an analogy is beneficial because it helps the student view the target in a more abstract way. In that view, by helping the student focus on the shared relational structure between the base and the target and downplaying the significance of the actual objects and surface level object attributes, the analogy is thought to help lend abstract relational structure to the previously poorly structured target situation (Gentner, 1983, 1989; Gick & Holyoak, 1983; Holland, Holyoak, Nisbett, & Thagard, 1986; Holyoak & Thagard, 1989). The learner is left with a mental representation of the target in which objects and object attributes are less salient and abstract relational structure is more salient.

By contrast, in the successful intervention in the book on the table study described earlier (Brown and Clement, 1989), the “atomic bonds as springs” analogy appeared to help *enrich* the students' conceptions of the target situations, rather than (or at least in addition to) helping them view the situations more abstractly. In this intervention, the concrete idea of elastic springs is projected into the microscopic realm to form an explanatory model of spring-like bonds between atoms. The student learns about a new, concrete mechanism that explains what is happening inside the targeted table system. It was hypothesized that this enrichment of the target with new objects, object attributes, and casual relations (e.g., microscopic bonds, flexibility and bending causing forces) is a very important means for conceptual re-structuring. Here, the dimensions of concreteness and generality become separated; the concreteness of the imagined mechanism does not imply a lack of generality. General, schematic models can be sparse in detail but still quite concrete in being dynamically imaged. As another example, the idea of swarms of moving molecules in a gas is concretely imageable, but the model is very schematic and general in the sense of being widely applicable. The fact that this model is hidden from observation does not mean that it is not concrete. In this view, the move in Table 1 from the observation pattern relations at Level 2, between temperature and pressure, to the explanatory model relations at Level 3, between molecular speed and impact on the walls of the container, is not a move from concrete to non-concrete imagery; rather, it is a move from one set of concrete images at the empirical level to an additional set of concrete images at the theoretical level. In this view, analogies and models can be a source of enrichment rather than a source of abstraction.

Brown, (1993) argued that analogies can help students “refocus core intuitions” by helping them to enrich their representation of the target. On the basis of in-depth interviewing data with students learning electricity via the pressure analogy, he argues that analogies can sometimes change the way the student’s “core intuitions” are projected into a target domain. This can be very important for sensemaking and retention, since other strong intuitions can be responsible for “unseating” newly learned target models (see also chapter by Brown and Hammer in this volume).

Contrasting diagrams. Thinking about model learning in biology offers a fresh perspective on the issue of abstraction, since abstraction is, in general, less pronounced in biology than in physics; in biology elaborated structures are a major focus. The models in the middle row of Figure 4 are somewhat abstract in that they are simplified, schematic representations of living organs of biomass. However, rather than seeing increasing abstraction as central to all model construction activity, in images of model evolution like those in Figure 4, conceptual change appears as the gradual revision and *enrichment* of initially simplistic models, a trend that can be considered in the opposite direction from abstraction. The use of concrete, scale models of molecules and of the solar system would seem also to work in this direction by adding more and more schematic, but concrete, structure.

On analogies vs. explanatory models. It is common to make such statements as “The billiard table is an ‘analogue model’ of the gas.” The previous sentence is acceptable if “analogue model” refers to “scientific model in the broadest sense”—in which case any constructed representation that can be used to think about the gas qualifies. But the sentence is not acceptable in the present framework if “analogue model” means an *explanatory* model. A scientist’s elastic-particle model of a monotonic gas is not the same as a billiard table. Certain elements have been added (tiny size, perfect elasticity, 3 dimensional motion, constant motion, etc) and subtracted (colors, external cause of motion, etc) from the original analogous case. We do not think of there actually being billiard balls inside of gases. I would prefer to say that the *analogous case* of the pool table can be used as a starting point for developing an *explanatory model* of a gas as a swarm of elastic particles. I will call this kind of analogous case a *proto-model*. By using different names for these two entities, their relationship can be discussed, something that is not often done in the literature.

### **How Analogous Cases as Proto-Models can support Explanatory Model Construction, Not Just Provide A Correct Prediction For a Target Problem: Harre’s View**

Hesse (1967) and Harre (1972) distinguish between the following:

- 1) An analogous case that shares only its abstract form with the target. (Hesse cites hydraulic models of economic systems as one example). Such a case may happen to behave like the target case and therefore provide a way of predicting what the target will do. But it does not explain how the target works. I call this an *expedient* analogy.
- 2) A model that has become, in Harre's terms, a "candidate for reality", such as the elastic particle model of a gas. In this case, a set of material—but hidden—

features, in addition to the abstract form, is hypothesized to be the same in the model and the target situation. (These features are often unobservable in the target at the time). In the elastic particle model a gas is hypothesized not only to behave like particles bouncing around, but to actually consist of something very much like tiny particles bouncing around. I refer to the latter kind of model as explanatory. Thiele and Treagust (2006) observed a number of analogies that I call expedient in their study of chemistry teachers' use of analogies, such as: activation energy is like a pole vaulter attempting a vault; and competing forward and reverse rates of a reaction is like a person walking up a down escalator. Here I call these expedient analogies because, although they are instructive, they do not introduce material elements as starting points for constructing an explanatory model.

**(Figure 5 about here)**

Triangular relation in model construction. An analogy can be viewed as involving two main elements: the target case and the analogous case. However, the above considerations mean that it is often desirable to take a three-element view of the relation between target, analogous case, and explanatory model, as in Figure 5. Pressure in a car cylinder can be explained roughly by analogy to a billiard table, but greater power comes from the development and refinement of an explanatory model, which can be thought of as our best estimate of nature's hidden mechanism in the gas. Clement (2008c) argues that such a model is neither deduced from axioms nor induced as a pattern from repeated experiences. Rather, it is abducted as a construction pieced together from various sources, including the billiards analogy, designed in such a way as to provide an explanation for the target phenomenon. As mentioned, Clement and Steinberg (2002) tracked the learning of a high school student as she was introduced to electric circuit concepts via an air pressure analogue. There is evidence that this was a proto-model since concrete features of air pressure differences causing air flow are transferred by her to the explanatory model as a starting point for thinking about how differences in "electric pressure" (voltage) cause current flow.

### **Roles Of Analogy**

The distinctions developed in the sections above allow one to discriminate between more purposes for analogies, as shown in Table 4, than are commonly recognized. These analogy types have been distinguished in expert protocols in Clement (2008c), but explicit comparisons of their uses in educational contexts is a task for future research. An exception is Cheng and Brown (2010) who studied elementary students' spontaneous analogies about magnetism, finding that many were expedient analogies but only a small number were protomodels.

Using an analogue as a proto-model. Earlier, I raised questions about the limitations of analogies as a lone strategy, saying that it might not deal with the student's prior model M1. Figure 3 depicts an improved strategy by showing how analogy can play the role of a proto-model as one source of material to help *modify* model M2. For example, a case of lower than ambient pressure such as a vacuum cleaner can be incorporated into an existing "pressure" model of electric potential to introduce the concept of negative voltage at one end of a battery. The intention is not to import the entire vacuum cleaner analogy into the model but primarily to contribute the "lower than

ambient pressure” idea. Their use in this contributory way is not “watered down” science, because a number of historians of science have described analogies as providing contributory elements during model evolution, such as Darden (1991), Nersessian (2002), Holland, et al. (1986), Millman and Smith (1997), and Gruber (1981).

Figure 3 can also be used to contrast this role for analogies with that of a bridging analogy or “domain expander” illustrated in Figure 1. In Figure 1 the bridging analogies are cases that are compared with each other and the target case. In the vacuum cleaner case and Figure 3 the proto-model analogy is not just a case to be compared with the target circuit but contributes a subschema that is incorporated into the explanatory model itself.

One can now hypothesize that analogies playing the roles in Table 4 may contribute selectively to different processes of conceptual change shown in Table 3. For example, the expedient analogue of a pole vaulter might be used to introduce the idea of activation energy for a reaction, but this does not really give an *explanation* for the relationship; therefore, its contribution to explanatory modeling is marginal. A domain-expanding, bridging analogy would naturally contribute to type (2) in Table 3, conceptual change via changing the domain of applicability for a concept, in Table 3. Using analogous cases as exemplars for abstraction naturally can contribute to (3) forming a general schema by abstraction. A proto-model analogue would serve as a starting point for (6) constructing a new initial model, or for adding a new component in (4) a major model modification. This mapping between types of analogies and types of conceptual change is not presently discussed in the literature, to my knowledge, and it suggests that different techniques for using analogies may be needed for different types of change. These considerations may eventually help us explain why previous studies have found mixed results in using analogies.

### **A Focus on Modeling as a Primary Purpose for Analogies**

One thing these distinctions can buy us is focus—the ability to focus on the development of the explanatory model as the most important content goal of science instruction. The central row in Figure 4 represents this development. The model, as a schematic, general, and flexible knowledge structure, is a more important outcome than the knowledge of any one analogy or case. Rather than being an endpoint in themselves, analogies are seen as one of several sources of ideas for initiating or developing an evolving explanatory model. Personally, I believe this to be the way to describe the most important role of analogy in science instruction. (Zietsman and Clement [1997] found that some *extreme cases* can play a similar role in supporting model construction. This is in opposition to the prevailing theory that the only major role of extreme cases is to provide a confident extra data point for inducing a pattern or testing a theory.)

This view is consistent with Glynn’s call for teachers to be explicit about the parts of an analogy that do not map to the target. Mason (1994) documents fifth grade students’ abilities to discuss the shortcomings of an analogy between postmen delivering letters and the blood cells delivering oxygen to other cells, which she sees as indicative of their increasing metacognitive awareness of the purpose of an analogy. When an analogy is viewed as one stepping stone in a longer process of model evolution, the “dangerous” disanalogous aspects can become valuable points for discussion that highlight distinctive features of the explanatory model—features that *contrast* to those in the particular analogy.

Returning to the positive side of analogies, what, if anything, is transferred from an

analogy to an explanatory model? Clement and Steinberg (2002) and Clement (1994, 2008c) hypothesize that it can include schema elements capable of generating dynamic imagery, citing, for example, case study evidence in which particular gestures for both pressure and flow appeared during their subject's work with the air pressure analogy and then reappeared during her work on instructional problems on circuits. They speak of this as transfer of imagery or "transfer of runnability". Hesse's idea that explanatory models involve mechanisms thought to have some material similarity to the hidden structure of the target is consistent with the idea that a central component of an explanatory model is an imagistic, or analog representation that preserves some of the structure of what it represents. The roles of imagery in analogy and explanatory model construction are important topics that I have not had space for in this chapter. It is examined in Bolger, et al. (2010), Gilbert, et al. (2008), Hegarty, et al., (2003), Nersessian (2002), Clement (1994, 2008c, 2009a, 2009b), Schwartz and Heiser (2006), and Schwartz & Black (1996b) among others.

In sum, analogies can play a *narrower* role in instruction for explanatory model construction than is assumed by some, in the sense that they are only one of many strategies needed for model construction (Figure 4). And in contrast to the prediction of the "big bang" theory of producing fast and large conceptual change via analogy, instructional analogies can require extended and careful development. Conversely, analogies can play a *wider*, more varied, more important role in instruction than is commonly assumed, in the sense that they may have more varied purposes than commonly recognized. It may be that different techniques are needed for using analogies for different purposes, such as those in Tables 3 and 4. This provides an important agenda for future research.

### **Conclusion**

The tables and figures in this chapter form the basis for a summary of findings on the relationships between analogies, explanatory models, and conceptual change. From history of science, we find that hypothesized hidden mechanisms, explanatory models are a separate form of knowledge from qualitative or quantitative patterns in observations (Table 1). The theoretical perspective of this chapter regards explanatory models as *the qualitative core of meaning for a scientific theory* and *the center of explanatory sense making for students*. It suggests refocusing curriculum development and instruction so that explanatory models are the central organizers for content goals. A variety of studies conclude that model presentation, dissonance, and analogy strategies can lead to positive results in conceptual change teaching under certain conditions. Figure 3 depicts the resulting image of model based instruction, a kind of model evolution with inputs from both students and the teacher, that has been used in several innovative curricula, involving repeated cycles of *model evaluation and revision*. Many other strategies can be used to support *model evolution* as depicted in Figure 4, in a process of teacher-student co-construction. This was described as a middle road between lecture and open-ended discovery learning.

Table 3 portrays a *large variety of types of conceptual change* identified by different researchers. Using these ideas, an idealized image of an approach to content based curriculum development begins from the identification of students' positive and



negative preconceptions in relation to a target model, leading to a planned *learning pathway* (shown in the central row of Figure 4). This prepares the way for research based lesson or unit planning by first, identifying the type of conceptual change being sought from those in Table 3, for a step in the pathway, then choosing teaching strategies at a finer grain size, such as those in the bottom row of Figure 4, to facilitate the conceptual change. Within a lesson, maintaining class discussions, or using student “voting” techniques and other ongoing assessments are ways to give the teacher enough feedback to decide how to keep students in a “reasoning zone”. To succeed, these cognitive considerations need to be combined with other considerations not dealt with in this chapter--such as ways to foster: social dynamics of large and small group learning, larger integrative and motivational contexts, students learning about the nature of models and science learning, and ongoing metacognitive self assessment. A theory positing *four basic purposes for analogy* was developed on the basis of expert studies and teaching studies. Two purposes were identified as especially important for explanatory model construction: analogies used for domain expansion and analogies used as proto-models. Subsequent model revision going beyond the original analogy, however, is deemed essential. This contrasts with a view of analogy as a simple short cut to understanding, and indicates that specialized teaching strategies may be important for different types of analogies to succeed.

Filling in other processes outlines an important agenda for future research. An initial example in this chapter is the attempt to map the four different types of analogy processes to the different types of conceptual change they can produce in Table 3. In future research we may be able to map other teaching strategies to different types of conceptual change. One can then imagine a form of top down curriculum planning that could occur, starting from research on students’ preconceptions and a learning pathway specifying the type of conceptual change that needs to happen at each juncture. It appears that a curriculum designer or teacher trying to decide how to teach a unit is going to encounter the need for many types of conceptual change. If we can understand what these types are, and what teaching strategies are particularly important for each, it will be a powerful advance in our theory of conceptual change instruction.

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**TABLES**

	<b>LEVELS</b>	<b>EXAMPLE: STUDY OF GASES</b>
<b>T H E O R I</b>	<b>4. Formal Theoretical Principles</b>	Principles of Thermodynamics
<b>E S</b>	<b>3. Explanatory Models</b>	Colliding elastic particle model
=====		
<b>O B S E R V A</b>	<b>2. Qualitative or Mathematical Descriptions of Patterns in Observations, including Empirical Laws</b>	$PV = kT$ (refers to patterns of observations of measuring apparatus)
<b>T I O N S</b>	<b>1. Primary-Level Data: Observations</b>	Measurement of a single pressure change in a heated gas

**Table 1. Four Levels of Knowledge Used in Science**

1. The base (anchor) may not be understood sufficiently
2. The base may be too far from the target for the student to see the mapping or to see its applicability to the target
3. The student may transfer too much from base to target ('overmapping')
4. The analogous case may not contain all of the relations needed to develop the target model.

**Table 2. Possible Limitations and Difficulties in Using Analogies in Instruction**



<b>CC Process</b>	<b>Example of Author</b>	<b>Outcome</b>
Paradigm Shift	Kuhn	Collection of ideas that differs drastically from original in multiple ways
-----	-----	-----
8) Branch Jumping and Tree Switching	Thagard, Chi	Replace concept w. ontologically different type of concept
7) Fundamental Concept Differentiation or Integration	Carey, Wiser	Fundamental concept split or concepts united
6) Construct New Initial Model	Mayer	Initial Model formed, with assumption that it has not grown out of an earlier model
5) Synthesis or Combination	Vosniadou, Collins and Gentner	Conjoined Models
4) Major Model Revision	Clement, Steinberg	Add, remove, or change element to produce revised Model
3) Abstraction	Gentner, Holyoak, Nersessian	General Schema formed from exemplars
2) Change in Domain of Applicability	diSessa	Model with new applicability conditions and exemplars
1) Minor Model Revision	Rumelhart and Norman's "tuning"	Adjusted Model

**Table 3 Types of Conceptual Change in Explanatory Model Development**

**Analogous Case As Exemplar For Induction Or Abstraction.** Example: several exemplars of acceleration may be given in order to develop the concept of acceleration. The exemplars are analogous to each other and may help students form an abstract concept of acceleration. Some may prefer to refer to this process as induction from exemplars rather than induction from analogy.

**Expedient Analogy.** Example: the behavior of an LRC circuit is analogous to the behavior of a weight oscillating on a spring, including the concepts of oscillation, amplitude, and damped oscillation. But there is no deep causal connection where elements of one system can be used as an explanatory model for the other in the sense of a mechanism viewed as actually operating in the other.

**Domain-Expanding Analogy.** Example: bridging analogies were used to expand the domain of application of the springiness idea in the book on the table lesson. (The form of this is shown in Figure 1). An analogy can be formed between two examples at the same level—that is, an anchoring analogous case and a target (e.g. the spring and the table)—which can encourage a student to stretch the domain of application of a correct intuition and apply it to the target example.

**Analogue as Proto-Model.** Example: using billiards as a starting point for the elastic particle model (shown in Figure 5) or using a camera as a starting point for developing an explanatory model of how the eye works (Glynn, 1991). Here, the anchoring, analogous case is used as a starting point, or building block, for adding to an explanatory model. The model is at a deeper, hidden, explanatory level than the observable target phenomenon, and the analogous case provides a piece of, or starting point for, developing the model. In contrast to analogy type one above, here the analogous case is not an exemplar of the explanatory model; e.g., a billiard table is not an exemplar of a gas.

**Table 4**  
**Four Types and Purposes Of Analogy**

## Captions:

Figure 1

Chain of bridging analogies transferring intuition from anchor to target

Figure 2

Combined strategy using analogies and dissonance together

Figure 3

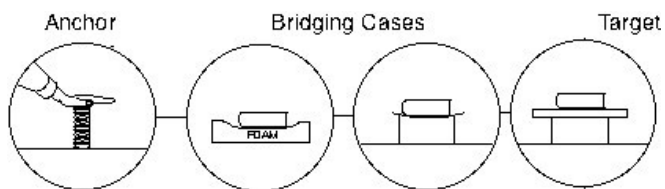
Evolution approach for teaching models

Figure 4

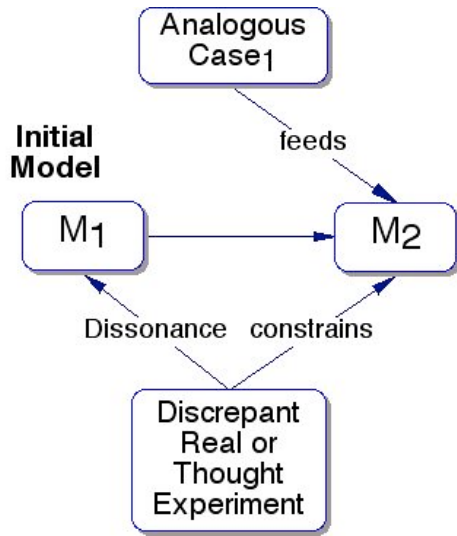
Model evolution from teacher-student co-construction

Figure 5

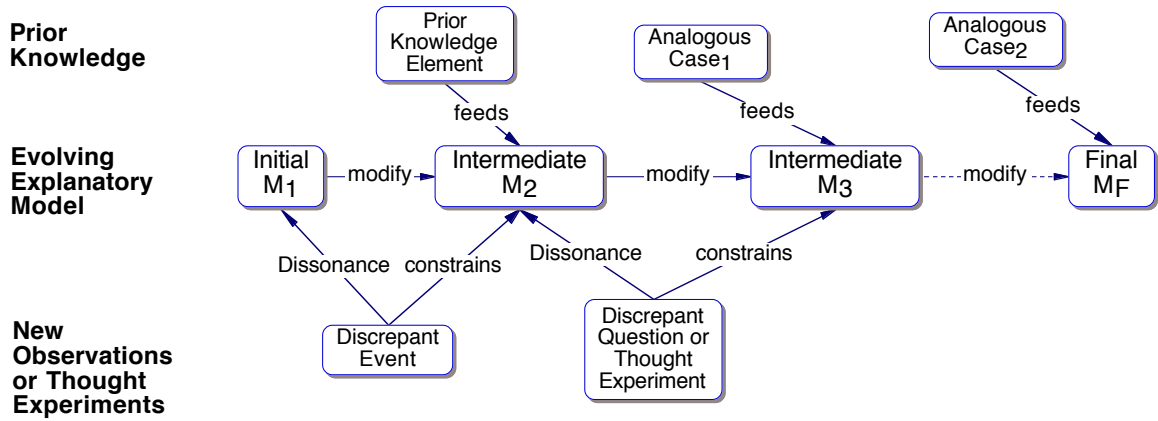
Three-element view of the relation between target, analogous case, and explanatory model



**Figure 1**



**Figure 2**



**Figure 3**

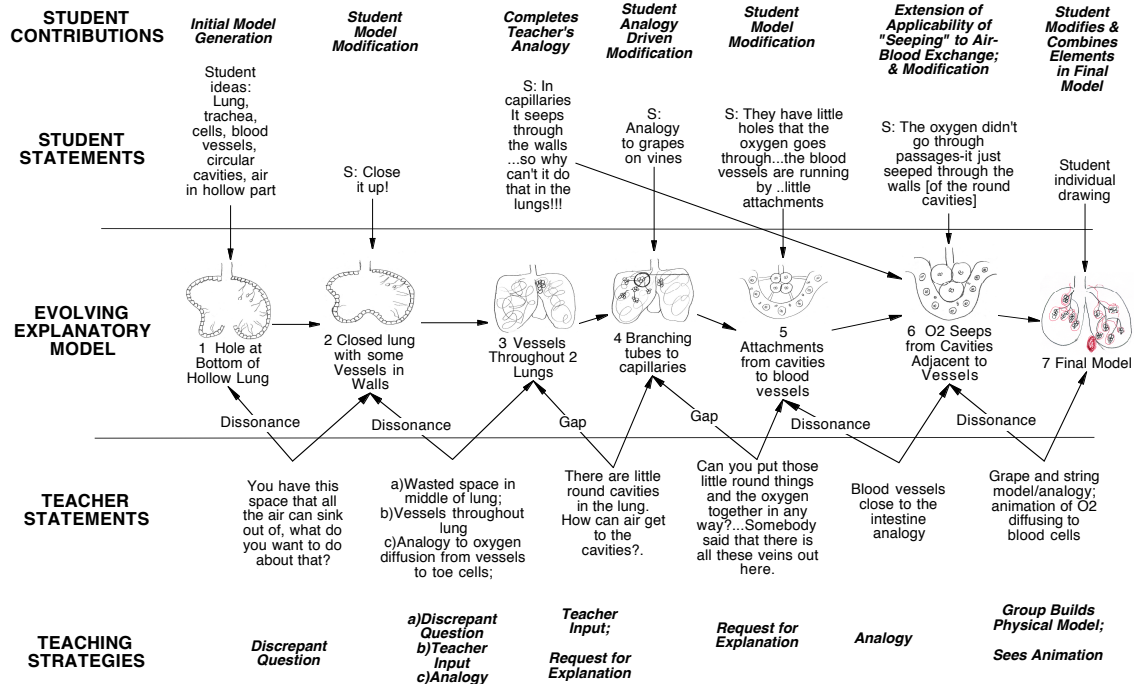


Figure 4

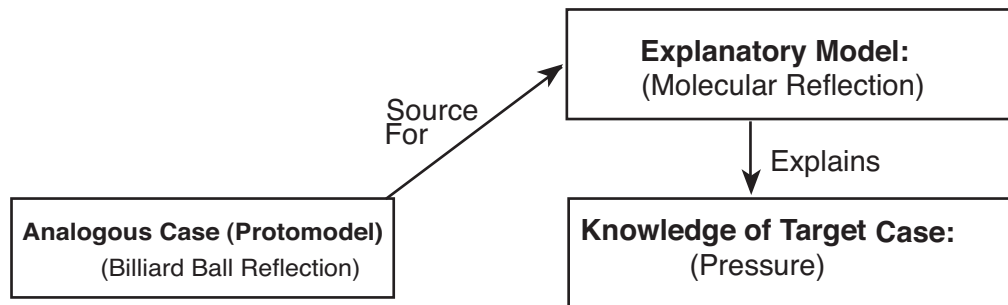


Figure 5