Modeling Theory For Paradigmatic Evolution

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Modeling theory promotes evolution of student paradigms about the physical world through mediated learning of scientific theory and inquiry. Students are guided through learning (modeling) cycles to structure the content of any scientific theory around a few basic models through insightful, reflective, and collaborative inquiry. Each cycle is devoted to the progressive construction and deployment of a specific model and its conceptual building blocks in accordance with particular modeling schemata and following particular modeling schemes. Modeling schemata constitute organizational tools for students to structure their conceptions meaningfully, and practical templates for teachers to plan and evaluate instruction efficiently. Modeling schemes foster development of tools, norms and rules of scientific inquiry in the context of appropriate activities conducted by individual and groups of students. Teachers mediate activities so as to help students detect and resolve any incommensurability with science that might emerge in the process. Students reach significantly higher levels of performance in their science courses under modeling instruction than under other forms of instruction.

Numerous movements have taken place in the last two decades to reform the state of mathematics, science and technology (MST) education worldwide. Reform has been called for following the alarming outcomes of local and international research on student knowledge in MST. Constantly throughout the second half of the twentieth century, such research has been basically showing that traditional MST courses do not bring students up to a meaningful understanding of course content. At best, most students who pass traditional exams do so only because of their capacity to recall theoretical statements and reproduce problem solving routines that they managed to memorize by rote and to retain in their memory for only a short time. In the meantime, research in cognitive science and the philosophy of science has been providing us with significant insight about expert and novice practices in MST, and urging us to bridge the gap between the two groups by bringing expert practices into the classroom. Many educators and concerned groups have in particular been advocating for modeling practices that MST experts resort to in their research (cf. Halloun, in press, for an extensive list of references).

Modeling theory is originally a theory of science promoted by philosophers of science and cognitive scientists. This author has been developing it into a theory of science education for the last two decades. The educational theory can be readily deployed into mathematics and technology education. It has originally been developed for physics curricula at the secondary school and college (university) levels (Halloun, 1984, 1994, 1996, 1998a, 1998b, 2000; 2001a; Halloun & Hestenes, 1987). It has recently been deployed into the broader field of science education (Halloun, in press).

Modeling theory in science education is grounded in a number of tenets. Some of these tenets draw on the philosophy of science and are about the nature of scientific knowledge and inquiry. Others draw on cognitive and educational research and are about learning processes in which students ought to get engaged in order to develop meaningful understanding of science. As discussed in this paper, the theory promotes a paradigmatic evolution whereby students transcend their naïve realism (or common sense) and evolve into the realm of science (section 1 of the paper). A special attention is paid for empowering students to structure the content of a scientific theory around a few basic models (§ 2) of well-defined structure (§ 3) and to develop stable skills of scientific inquiry (§ 4). The evolution is student- centered, teacher-mediated (§ 5). It is promoted through learning cycles (§ 6) that are structured enough to keep student activities and their by-products in line with scientific theory and inquiry, yet flexible enough to account for differences in students' initial knowledge state and to allow for insightful self-regulation. As such, modeling theory has constantly shown its efficacy when deployed in science education and especially in physics courses at the secondary school and college levels (§ 7).

1. Paradigmatic evolution

In 1910, Dewey argued that "the future of civilization depends upon the widening spread and deepening hold of the scientific habit of mind…, [the kind of habit] that to some extent the natural common sense of mankind has been interfered with to its detriment…; the problem of problems in our education is therefore to discover how to mature and make effective this scientific habit" (Archambault, 1974, pp. 190, 191). About a century later, and despite numerous similar calls worldwide, Dewey's "creed of life" is not fulfilled yet. The reason is partly because, as Dewey argued, "science has been so frequently presented just as so much ready-made knowledge, so much subject-matter of fact and law, rather than as the effective method of inquiry into any subject-matter… a method of thinking, an attitude of mind, after the pattern of which mental habits are to be *transformed*" (ibid, pp. 183, 187, italics added).

The transformation Dewey is calling for is, from our point of view, a comprehensive transformation in student *natural paradigms**, i.e., paradigms about the physical world. It is a paradigmatic evolution from the realm of naïve realism or common sense to the realm of science. This entails an evolution of all aspects of student paradigms, aspects that extend from underlying canons to various conceptions (concepts, laws, and other theoretical statements), tools and processes, and that encompass various cognitive factors that affect learning.

Educational research on students' inquiry and conceptions about the real world reveals that their natural paradigms have many components that differ significantly from those of scientific paradigms, and that they are by far not as systematically, reliably or coherently articulated as their scientific counterparts. This should come of no surprise to us. Students are not afforded in their everyday life, or even at school, the sort of physical environment or the kind of social interaction that scientists are afforded in their observatories, research facilities and professional organizations. In this respect, scientists and students live in different worlds, and the two groups are driven by two different cultures (Cobern, 1995) of different goals, commitments, concerns and requirements (Reif & Larkin, 1991).

To each scientific paradigm corresponds a variety of student natural paradigms, and this, irrespective of the demarcation lines we might draw between various scientific paradigms. A student paradigm often consists of a mix of components some of which may be somewhat compatible with modern scientific paradigms, others at odds with the latter and often reminiscent of paradigms that dominated the pre-Galilean era of science, and that relied heavily on common sense, perceptual experience (Cobern, 1993; Halloun, 1986; Halloun & Hestenes 1985a; Helm & Novak, 1983; Novak, 1987, 1993).

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* A paradigm is, for us, a conceptual system that governs explicitly a person's conscious experience in a given situation as follows (Halloun, in press):

1. It determines the conditions that trigger every voluntary activity in the experience.
2. It sets forth standards, rules and guidelines for choosing and processing all that is necessary for the reification and continuous evaluation of the activity. This includes selection and analysis of empirical data when the experience is with physical realities.
3. It provides necessary conceptions, conceptual tools and methodology for conducting the activity and for refining the paradigm subsequently.
4. It supplies appropriate mnemonics for consciously retrieving necessary means and method from memory.

An alternative look at student natural paradigms is offered by Bachelard (1940) and Mortimer (1995) whose works imply that nobody holds a single natural paradigm, but that every human being, whether a student or a scientist, holds a mix of natural paradigms, some in agreement with science others at odds with it. These paradigms make up the person's *paradigmatic profile*. Various components of a paradigmatic profile may be at different levels of maturity and complexity depending on the individual's personal experience. Depending on such experience, a given conception may be confined to a single paradigm, or it may have different alternatives distributed across different paradigms (Halloun, in press).

A scientist paradigmatic profile is dominated by two broad dimensions, i.e., two broad paradigms, one governed by *classical* scientific realism (CR), the other by *modern* scientific realism (MR). We speak of scientific *realism* because scientific conceptions *correspond* to physical realities, and each conception *represents* a set of these realities in specific respects and to a certain extent. This does not ignore the fact that scientists invent their conceptions (just like ordinary people do) in order to *re*construct, in a convenient way, what they represent in the real world. The viability of each dimension (CR or MR) is well-established by a concerned scientific community within well-defined scopes and limits of approximation, and the two dimensions complement one another in specific respects. A physicist may use a Newtonian model (from a classical paradigm) to study the motion of a given physical object, and then shift to a relativistic (modern) model to study the same motion or a similar one, should s/he desires to significantly improve the precision of the outcomes. In contrast, paradigmatic profiles of ordinary people, students in MST courses included, do not have their scopes and limits of viability well delineated, and various paradigms often overlap one another in conflicting ways. A student might have recourse to a particular model when studying a given movement (say, a positivist model), and then to a contradictory model (say, a classical, Newtonian one) when dealing with a similar movement actually governed, from a scientific perspective, by the same model.

Of the two broad dimensions mentioned above, the paradigmatic profile of an ordinary person seldom includes a modern one. Still, no scientific dimension, including the classical one, can be as important for an ordinary person as it is for a scientist. Hence, while the profile of a scientist is dominated, to variable degrees, by CR and MR, the profile of an ordinary person often consists of an unbalanced and incoherent mix of paradigms governed by *naïve* realism* (NR) or some sort of classical realism (CR). We refer to the latter mix: (a) as common sense (CS) profile, when there is some balance between NR and CR, and (b) as naïve profile, when it is dominated by NR (Figure 1). Similarly, a non-scientific natural paradigm is referred to as naïve paradigm when dominated by NR, and as common sense paradigm when underlined somewhat more by CR than NR. A person with a naïve paradigmatic profile is called naïve realist.

What corresponds to a given science course in the dimensions of a student paradigmatic profile (mostly NR and CR) varies in content and size from one course to another, depending the nature of the physical realities involved, and on student familiarity with these realities. The corresponding naïve realism dimension often consists of two parts. The first NR part corresponds to situations where the expressed naïve ideas may be locally coherent in the sense that they may allow apparently consistent inferences in closely related domains; these ideas may be considered as viable (with trepidation) when confined to these domains (Reif & Larkin, 1991). Some of the viable ideas might still be at the level of

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* A good proportion of naïve realists hold, in many respects, a positivist perspective on physical realities, and believe mistakenly that modern science does the same. They believe that salient features of physical realities are exposed directly to our senses and that human knowledge, including scientific knowledge, mirrors the apparent world. Many of them believe, like Mach, that scientists do not admit the existence of any physical reality unless they can perceive it directly with their bare senses or with some instruments ("esse est percipi"). Naïve realists also maintain that one should, and can, observe physical realities without any influence of prior knowledge, and this in order to guarantee the objectivity of constructed knowledge. In this respect, they believe that scientists collect and analyze empirical data in an inductive Baconian approach, without any à priori hypotheses or any à priori judgment regarding primary (salient) and secondary (inconsequential) details they need to concentrate on (Halloun, in press).

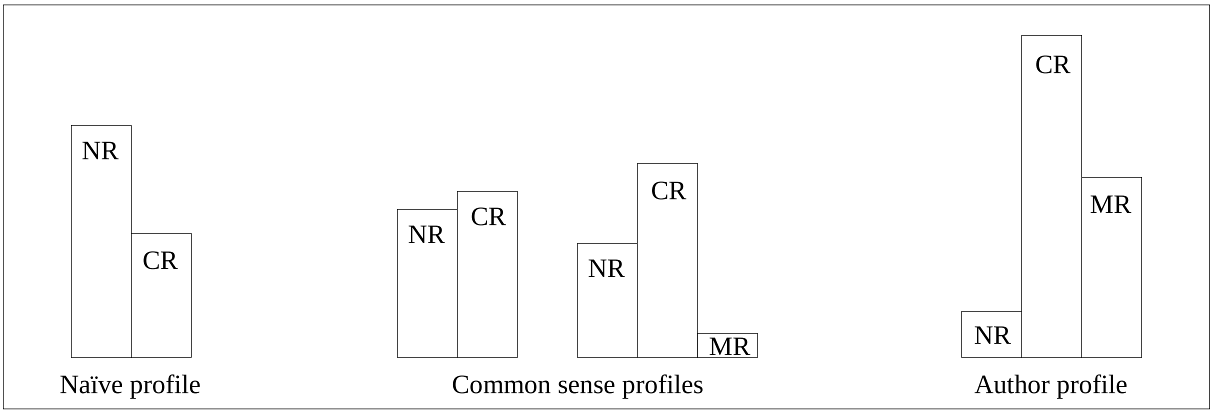

Figure 1. Paradigmatic profiles (Halloun, in press).

Bars are not to scale in the above bar charts, and bars' relative heights reflect an ordinal and not a proportional order of magnitude.

My own natural paradigmatic profile is currently dominated more by classical scientific realism (CR) than by modern scientific realism (MR) because my professional experience has so far been concerned more with CR than with MR. The naïve realism (NR) dimension is mostly about physical realities that are the object of scientific fields outside my domain of expertise, and which I casually contemplate.

uncorroborated beliefs, while others could have already been corroborated in some respects, though insufficiently, in the student personal experience. The second NR part corresponds to situations where naïve realism could not apply under any circumstance, and where CR could be more appropriate from a scientist perspective. Like the first part, this one includes uncorroborated beliefs, as well as other ideas that appear to be duly corroborated in the student mind but whose claimed evidence is actually unreliable or not conforming to accepted scientific theory. The NR dimension is thus incoherent, and it often leads to inconsistent inferences and contradictions.

In contrast, the CR dimension of a student paradigmatic profile consists of ideas that are all relatively viable. The size of this dimension by correspondence to a given science course is evidently smaller for students than for scientists concerned with the content of the course, and the more remote the course is from everyday life, the smaller the CR dimension in student profile. Needless to say that viability is not ascertained here to a high degree of rigor. A component of a student profile is considered "viable" only to the extent that it is closer to a scientific viewpoint rather than to a naïve one.

The mismatch between student and scientist natural paradigms takes in many respects the form of a "clash of cultures". For many students, and especially naïve realists, science looks like a foreign culture that is being forced on them and that can only be met with resistance (Cobern, 1995). At best, students resign themselves to the authority of teacher and textbook and learn things by rote only to satisfy curriculum requirements. They often end up with a sort of *cognitive dissonance* between what they learn in science courses and the way they interact with physical realities of everyday life, a way that remains mostly driven by naïve realism. The dissonance is often so deep that no educational theory or schooling system can ever entirely close the gap between naïve realism and its scientific counterparts. We do not claim that modeling theory can do so either. In fact, no formal education should even consider a radical paradigmatic evolution (or paradigmatic shift in the Kuhnian sense) whereby secondary school or even college students transform their common sense or naïve paradigms entirely into scientific paradigms. A more reasonable credo is to *transform naïve and common sense paradigmatic profiles*, and not paradigms, into more viable profiles whereby the naïve dimensions (NR in Figure 1) would be significantly reduced in favor of scientific dimensions (mainly CR in this figure).

Eliminating naïve realism (NR) altogether from any person's paradigmatic profile would be a far-fetched target for many reasons discussed elsewhere (Halloun, in press). As suggested by Bachelard (1940) and Mortimer (1995), educators should instead concentrate on: (a) making students realize the limitations of the naïve part of their profile, and thus (b) the necessity to build up the viable counterpart in the scientific direction. Modeling theory calls for an evolution of students' paradigmatic profiles along these lines, an evolution that significantly reduces the naïve realism dimension and that raises the classical and modern scientific realism dimensions to *realistic levels*. These levels, as we shall argue next, correspond to what we call basic models in any scientific theory that is the object of a science course.

2. Middle-out theory structure

Many cognitive scientists have shown that, in accordance with the theory of prototypes and basic-level categories of Eleanor Rosch, "categories are not merely organized in a hierarchy from the most general to the most specific, but are also organized so that the categories that are cognitively basic are 'in the middle' of a general-to-specific hierarchy… Categories are not organized just in terms of simple taxonomic hierarchies. Instead, categories 'in the middle' of a hierarchy are the most basic, relative to a variety of psychological criteria" (Lakoff, 1987, pp. 13 and 56). For example, "dog" is "in the middle" of a hierarchy between "animal" and "retriever", just as "chair" is between "furniture" and "rocker" (Figure 2). Categories in the middle (e.g.) are *basic* in the sense that: (a) they ensure best a cohesive structure of human knowledge of any type, and that (b) they constitute the most accessible, efficient and reliable building blocks in knowledge construction and deployment.

Categories Hierarchy (according to Eleanor Rosch & George Lakoff)		
SUPERORDINATE	Animal	Furniture
BASIC LEVEL	Dog	Chair
SUBORDINATE	Retriever	Rocker
Real World Structural Hierarchy:		
SUPERORDINATE	Matter	Galaxy
BASIC LEVEL	Atom	Solar System
SUBORDINATE	Elementary particle	Planet
Conceptual Hierarchy in a Scientific Theory:		
SUPERORDINATE	Theory	
BASIC LEVEL	Model	
SUBORDINATE	Concept	
Model Hierarchy:		
SUPERORDINATE	Emergent model	
BASIC LEVEL	Basic model	
SUBORDINATE	Subsidiary model	

Figure 2. Middle-out hierarchies.

The middle-out hierarchy extends, from our point of view, from physical systems in the real world to conceptual systems in the paradigmatic world as indicated in Figure 2. Scientific theories provide the "content" core of a scientific paradigm, and models are 'in the middle' of conceptual hierarchy, between theory and concept. A *scientific theory* consists, for us, of: (a) a set of models or families of models, and (b) a set of particular rules and theoretical statements that govern model construction and deployment and that relate models to one another and to specific patterns in the real world. A *scientific model is a representation of a specific pattern* in the real world. The pattern may be about the structure or the behavior of a number of physical systems, systems spread out throughout space and time in the universe. The model is a conceptual system mapped onto the physical pattern in the manner described in the following section of this paper. Mapping is done so that the model captures only the essence of the pattern, essence consisting of only *primary* features that are salient to the model function, and not all details in the systems generating the pattern. The model may serve to: (a) describe, explain, and predict (or postdict) the pattern in question, and, eventually (b) control or change physical realities exhibiting the pattern, and (c) reify the pattern in new realities.

The model-centered, middle-out structure of scientific theory ensures theory coherence and consistency from an epistemological perspective, and it facilitates the development of scientific knowledge from a cognitive perspective. A scientific model is to theory and concept what an atom is to matter and elementary particles respectively. Each elementary particle is essential in the structure of matter, but its importance cannot be conceived independently of its interaction with other particles inside an atom. It's the atom and not elementary particles that give us a coherent and meaningful picture of matter, and it's the atom that displays best the role of each elementary particle in matter structure. Now, Bohr's model of the atom is essential for understanding hydrogen-like atoms, and is often referred to as a "model" in physical science textbooks. However, other scientific models are seldom referred to or even presented as such, which would give students the false impression that Bohr's model is about the only scientific "model". Furthermore, various concepts and laws are often presented episodically, one after another in a given chapter, without relating them to one another in the context of appropriate models, whether implicitly or explicitly. Students are thus deprived of the opportunity of developing a coherent, model-based, picture of scientific theory, and end up with a piecemeal, fragmented picture of the world. To get a feel of this picture, imagine what your knowledge about physical realities would look like should you've learned at school that matter consists of elementary particles and no mention was ever made to you about the atom.

Models in a given scientific theory can also be categorized in a middle-out hierarchy as shown at the bottom of Figure 2. In the middle of model hierarchy are basic models. A *basic model* is one that is simple enough to facilitate student understanding of fundamental tenets and conceptions (concepts, laws, etc.) of the respective theory and development of fundamental tools, skills and habits of scientific inquiry. Yet a basic model is generic enough to serve in the construction of more complex models in the theory. The set of basic models in Newtonian theory are given in Figure 3. A student needs to understand the entire set of basic models so that s/he could meaningfully learn the respective scientific theory, and realize a meaningful paradigmatic evolution.

At the subordinate level of the category of models are subsidiary models. A *subsidiary model* is a simplified basic model, a particular case that students may usually be most accustomed to in their everyday life and that can serve as a stepping stone for the comprehensive construction of the basic model in question. For example, the model of a particle in free fall (objects falling in vacuum in the absence of any force except for gravity) is a subsidiary model in Newtonian theory. It serves in the manner described in sections 5 and 6 of this paper for the progressive construction of the uniformly accelerated particle model (Fig. 3). At the superordinate level of the model category are emergent models. An *emergent model* is one that may be constructed by putting together two or more basic models in order to represent a pattern that cannot be represented by either basic model separately. The model of a bound particle in uniformly accelerated circular motion is an example of emergent models. It emerges from combining two basic models in Newtonian theory, the uniformly accelerated particle model and the bound particle in uniform circular motion (Fig. 3).

Free particle
Physical objects subject to no net force ($\Sigma \boldsymbol{F}_i = 0$), and thus maintaining constant velocity in any inertial reference system ($\boldsymbol{a} = 0$, $\boldsymbol{v}$ = constant).

Uniformly accelerated particle
Physical objects in linear or parabolic translation with constant acceleration ($\boldsymbol{a}$ = constant) under a net constant force ($\Sigma \boldsymbol{F}_i$ = constant).

Bound particle in harmonic oscillation
Physical objects undergoing periodic back and forth translation (sinusoidal $\boldsymbol{a}$ function) under a net force that is proportional to their displacement from a center of force ($\Sigma \boldsymbol{F}_i \propto \Delta \boldsymbol{r}$). This model is often called simple harmonic oscillator.

Bound particle in uniform circular motion
Physical objects in uniform circular translation ($a = v^2/r$) under a net centripetal force ($\Sigma \boldsymbol{F}_i \propto \boldsymbol{r}/r^2$) of constant magnitude.

Particle under impulsive interaction
Physical objects whose linear momentum changes significantly, and almost instantaneously, like in the case of collision, under a variable net force ($\Sigma \boldsymbol{F}_i = \boldsymbol{f}(t)$) exerted for a very short period.

Figure 3: Basic particle models in Newtonian theory of classical mechanics, with an outline of the translational pattern that each model represents in inertial reference systems.

Particle models refer to physical objects the internal structure of which can be ignored when they are in *translation* without rotation or precession, in a specific reference system. Each *basic* particle model is made up of a single, dimensionless object: a particle.

Some cognitive scientists, linguists and other researchers have argued that model-centered epistemology is not restricted to scientific paradigms, but that it extends to all sorts of human knowledge, and even to that of some animals (Johnson-Laird, 1983, p. 405 ff.). Bower and Morrow (1990) argue that “we build mental models that represent significant aspects of our physical and social world, and we manipulate elements of those models when we think, plan, and try to explain events of that world”. Meanwhile, Johnson-Laird, Hestenes and others express a more radical position. According to Johnson-Laird (1983, p. 402), “all our knowledge of the world depends on our ability to construct models of it”, and according to Hestenes (1995) “we come to know real objects (their properties and processes) only by constructing models to represent them in the mind” [italics added]. A more moderate position is expressed by Lakoff (1987) who argues that we “use cognitive models in trying to understand the world. In particular, we use them in theorizing about the world, in the construction of scientific theories as well as in theories of the sort we all make up” (p. 118). “The main thesis” of Lakoff’s work “is that we organize our knowledge by means of structures called idealized cognitive models, or ICMs” (ibid, p. 68).

In an analysis of categorization data, Lakoff (1987) shows, and Giere (1994) supports, that human categorization is based on ICMs and not on similarity between individual features. ICMs not only govern the middle-out hierarchy among categories, but they also imply similar graded structures within individual categories. In the latter respect, Giere (1994) argues that models of any scientific theory can be graded with some basic models in the middle. Giere’s argument supports our position that basic models are most important to develop the fundamental building blocks of a given scientific theory and corresponding rules of model construction and deployment. They thus need to be given a special attention in science education.

3. Modeling schemata

The effectiveness of a person's knowledge and the efficiency with which it is retrieved for deployment in particular situations depend primarily on the way this knowledge is organized in memory. That is why we pay in modeling theory a special attention to the way the content of a science course ought to be structured both in textbooks and in students' minds. More specifically we ensure that a scientific theory that is the object of a given course is structured around a set of models in the most explicit and systematic way possible. The content of a course would then consist primarily of a number of chapters each devoted to the formulation of a particular model along with necessary tools and rules of engagement. The most important of these tools are organizational tools that we call modeling schemata.

A *modeling schema* is an organizational template used to ensure that any conception, and especially a model, be built comprehensively without missing any primary feature, and that it be integrated coherently in a given theory, all this in the most efficient, compact and coherent way possible. It also offers, directly or indirectly, well-defined rules for evaluating and employing the corresponding scientific conception. In a sense, modeling schemata are, along with other tools, to meaningful learning of science what semantics and syntax are to mastering any language. A modeling schema sets the rules of correspondence of a conception to the real world just like semantics do with vocabulary. It also sets the guidelines for putting the conception together with, and relating it to, other conceptions just like syntax in grammar.

Two modeling schemata are especially helpful for teaching science. One is the model schema, the other is the concept schema. The model schema is a four-dimensional template. Two of the four dimensions, composition and structure, set the ontology and function of the model, and the other two, domain and organization, set its scope, all in terms of the scientific theory that the model belongs to, and by correspondence to physical realities exhibiting the modeled pattern.

The *domain* of a scientific model includes all physical realities exhibiting the pattern in question. These realities are called model *referents*. A model's domain can be delineated by answering questions of the sort:

- What physical systems does the model refer to in the real world?
- What pattern do these systems share in their structure and/or their behavior?
- Under what physical conditions?
- Under what limits of approximation and precision?

Model *composition* consists of concepts representing constituents and respective properties of physical systems that are salient to the pattern, along with corresponding depictions. Concepts are mainly of two types. Concepts of the first type are *object-concepts* (or conceptual objects). They represent physical bodies that significantly contribute to the generation of the pattern represented by the model. These may be *objects* that enter in the make up of each physical system of interest, or *agents* in the environment of the system, i.e., physical bodies outside the system that interact significantly with objects inside. Concepts of the second type are *property-concepts* (or *descriptors*). They represent salient physical properties of objects and agents, and of their mutual interaction. The composition of a model can be determined by answering questions like:

- What are the salient objects of a system and what object-concepts can represent them? (e.g., a particle in Newtonian mechanics, a dimensionless object, a point, that refers to physical objects whose translational motion is not affected by their geometric properties of shape and dimension).
- What are the salient agents in the respective environment and what object-concepts can represent them?
- In what kind of coordinate system can these objects and agents be most conveniently studied?

- What intrinsic descriptors (property concepts) characterize each object? (e.g., mass, charge).
- What state descriptors characterize each object? (e.g., position, momentum and other kinematical concepts).
- What interaction descriptors characterize object-object and/or object-agent interactions? (e.g., force, field and other dynamical concepts).
- What symbolic, pictorial, diagrammatic, graphical representations can most conveniently be used to depict all objects and descriptors above?

Model *structure* spells out relevant relationships among salient features of the pattern represented by the model. Model structure can be defined along four subdimensions, or facets, each dealing with a specific aspect of model referents in relation to pattern formation. These are the topology facet, the state facet, the interaction facet, and the cause-effect or causal facet. Each facet is distinguished conceptually by the nature of descriptors involved and the ways they are related in space and time. Various relationships are expressed in an appropriate reference system relative to which the pattern is conveniently identified. Such relationships come primarily in the form of laws that set the distinctive descriptive and/or explanatory *function* of the model. The structure of a model can be generated by answering questions like:

- What descriptive and/or explanatory function does the model serve? (e.g., a kinematical or a dynamical model).
- What geometric structure does the model have? (e.g., none for a particle model made of a single particle, topography of many-particle models). This question sets the *topology* of the model.
- What *state* laws describe best the behavior of each object? (e.g., so-called kinematical equations of motion, like r(t)).
- What *interaction* laws quantify best the interaction of each object with other objects and agents? (e.g., Newton's law of universal gravitation, Hooke's law).
- What *causal* laws explain best the behavior of each object? (e.g., Newton's second law).
- What symbolic, pictorial, diagrammatic, graphical representations can be used to depict all the above conveniently?

Model *organization* situates a given model in the respective scientific theory. It establishes the relationship of the model in question to other models in the theory by answering questions of the sort:

- What are the limitations of the model?
- What features does it share with other models in the theory that it belongs to?
- How does it differ from other models?
- What other models complement it in the theory?
- Can it be merged with other models to form a new model that answers questions that cannot be answered with either model separately? If so, how?

Concepts are elementary building blocks of models. They gain their significance only when used in model construction, and more specifically in spelling out laws, definitions and other theoretical statements that make up the model structure. In order to build concepts comprehensively and integrate them coherently into respective models and theory, the model schema is complemented with the *concept schema*. This is a four-dimensional template used for the construction of individual concepts within the context of basic models. The four dimensions are scope, expression, organization and quantification. They are concisely presented below for property-concepts or descriptors.

A descriptor represents, to a certain degree and within certain limits, a particular physical property shared by many real world systems or phenomena. It has a domain confined to the represented property and a particular function (descriptive or explanatory) depending on the nature of the property. Domain and function constitute concept *scope*. A set of *correspondence rules* establish viability conditions of the concept in the real world as well as its utility in the composition of models.

Each concept is expressed in science in a unique, and thus objective, way along with particular semantics that establish what the expression actually delineates in the real world or the rational world of scientific theory and paradigm. A mix of verbal, symbolic, iconic, and especially mathematical forms of *expression* is commonly used to communicate any scientific concept. The mix is necessary to come as close as possible to a comprehensive expression of the concept, since no single form can actually do so alone.

A descriptor gains its significance only after related to other descriptors within the contexts of models, and especially basic models. Concept *organization* sets criteria and guidelines for classifying a concept and for relating it to other concepts, all along with appropriate syntactic rules.

A descriptor cannot be scientific unless it is measurable according to well-defined *quantification* laws and rules. These set the sort of measurement that the descriptor can be subject to (nominal, ordinal, interval or ratio), and the means and procedures one can resort to for determining values of the concept on a certain scale, and by comparison to a certain standard.

Modeling schemata are as much helpful for science teachers as they are for students. They are used for planning and teaching lessons, and for assessing student learning and teaching practice. Under modeling instruction, the content of a teaching unit is usually organized around a specific model. Planning and teaching a lesson following modeling schemata ensure that students develop the model in question (or any necessary conception) without missing any salient feature. The same schemata can subsequently be used to develop an appropriate assessment taxonomy that covers all salient features, and that help logging the evolution of every student.

In the form presented above, modeling schemata are meant for immediate use more for teachers than for students. They serve as comprehensive templates or check-lists for planning, carrying out and evaluating instruction, and for putting more structure and coherence in the presentation of various models, laws and concepts in any scientific theory. Students need to systematically construct their conceptions following these schemata, but they need not, at least for a start, to do so by going linearly and explicitly through each of the four dimensions of a given schema. In fact, a schema and its dimensions should not even be presented as such to students, at least not freshmen. As instruction progresses, teachers may encourage students to develop, for each schema, some sort of a flowchart or check-list for comprehensive model or concept development.

4. Modeling inquiry

The paradigmatic evolution promoted in modeling theory is about both content and processes. At the epistemological level of knowledge content, it is about schematic (relative to schema) organization of a scientific theory around basic models. At the level of methodology, it is about the development of necessary tools and processes for scientific inquiry and associated rules of engagement, all of which are set by appropriate scientific theory and paradigm. The most important processes, from our perspective, can be classified in two categories: (a) *construction* of a new model, along with its validation, in the context of particular real world situations in order to represent a given pattern in this world, and (b) *deployment* of an already constructed model for solving empirical or rational problems.

The two modeling processes, model construction and model deployment, complement one another and are systematically and progressively developed, along with necessary tools and rules, through well-structured learning cycles described in § 6. It is true that model deployment follows chronologically model construction, i.e., it takes place after a model is being formulated in one form or another. However, model deployment does *not* strictly follow *from* model construction and it does not subserve the latter. The two modeling processes complement one another with respect to helping students develop a scientific model as comprehensively as possible, and gradually evolve into the realm of science. Model construction is not a one time shot, especially not when it follows the model schema. Such schema requires that a model be constructed in a *spiral* approach whereby the empirical scope of a model (domain and function) and its rational weaving (composition and structure) be developed progressively in the context of empirical and rational situations of increasing complexity. Model construction proceeds from the start, and all the way through, as a series of inquiry activities in both the empirical world of physical realities and related data and the rational world of scientific theory and paradigm. As such, the process of model construction follows the same canons of engagement with the two worlds as model deployment. On the other hand, model deployment offers learners a more flexible and effective platform than model construction to consolidate various modeling tools and rules, including but not limited to those that govern insightful and regulatory negotiations within and between the rational and empirical worlds (§ 5).

In modeling instruction, students are sometimes called to develop some prescriptive, generic schemes for modeling inquiry. Such *modeling schemes* emphasize the central role of models in all sorts of empirical or rational inquiry, including traditional problem solving for which the scheme of Figure 4 is devised. The strategy outlined in this figure starts by analyzing a problem givens (before identifying goals or reading questions) in order to choose, in an appropriate theory, the model(s) that can best represent the situation at hand. Once models are chosen, and only then, one can identify the problem goals in order to pick whatever is necessary for solving the problem from the model composition and structure, and then represent the chosen components mathematically in convenient, multiple ways (diagrams, equations, graphs, etc.). A mathematical model is thereby constructed that will next be processed in order to reach a solution to the problem. Every step of the way is evaluated by correspondence to the empirical situation, and in terms of the chosen theory, in order to ensure the validity and viability of the step. The process ends with a paradigmatic synthesis that recapitulates all major lessons learned in solving the problem, along with their implications on deployed models. This may include possible refinement of models and respective theory. Modeling schemes like the one in Figure 4 are primarily meant to help students realize that the solution to any problem can be efficiently attained by identifying (or adducing) at first the appropriate model(s) for the situation. Once the model(s) identified in a given problem, the answer to any question follows directly from model structure (provided that one has already developed such a structure following the model schema).

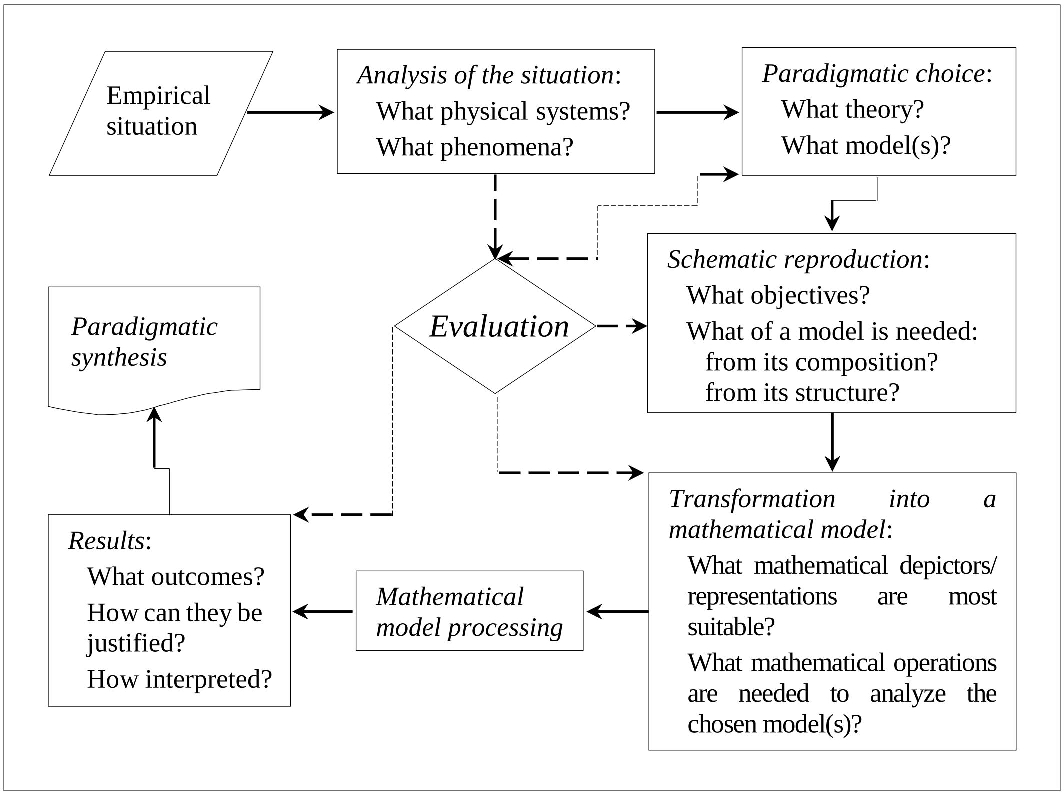

Figure 4. Model deployment in an application activity.

Table 1 : Modeling problems taxonomy (Halloun, 2000)

Problem type	**Required dialectics**	**Objectives**
Application	Empirical→Rational	Recognize real world situations that belong to the domain of a model and apply its composition and structure for the description, explanation and/or prediction of the state of physical objects in these situations.
Analogy	Empirical→Empirical	Develop criteria for establishing the analogy between real world systems belonging to the domain of a given model (model referents), and apply these criteria for designing new referents by empirical analogy.
Reification	Rational→Empirical	Invent new referents using exclusively a model composition and structure as conceptual blueprints (e.g., design a physical situation that matches some mathematical diagrams representing the kinematics or dynamics of a particle model in Figure 3).
Extrapolation	Rational→Rational	Analyze the composition and structure of a given model (or family of models) in order to refine the model, and perhaps propose new concepts or laws, or construct a whole new model; predict the existence of some unfamiliar situations in the real world following a thought experiment or the theoretical completion of a physical pattern.

Model deployment activities are not limited to conventional end-of-chapter paper-and-pencil problems. They include, like in the case of model construction, observations in the real world, empirical experiments, thought experiments (à la Galilée), field projects, case studies, all chosen with a special attention to interdisciplinarity and designed to provide, every now and then, the opportunity for team work. Most importantly, deployment activities are not limited to the "application" of conceptual models in solving empirical problems. They involve a variety of *dialectics* within and between two worlds, the *empirical* world of physical realities and related data, and the *rational* world of scientific theory. In other words, model deployment activities are not confined to exercises of exploratory inquiry as in conventional instruction, exercises limited to the application of specific theoretical statements to certain physical or fictitious realities. Instead, activities are diversified so as to help individual students develop a balanced diversity of skills pertaining to both *exploratory* and *inventive* research, while they meaningfully realize, and take advantage of, the potentials of every model in a given scientific theory. As such, modeling instruction maintains a balance between four categories of model deployment activities. Each category involves a particular type of dialectics within the rational world or the empirical world, or between the two worlds. The four categories outlined in Table 1 are: application, analogy, reification, and extrapolation.

Throughout the processes of model construction and deployment, students develop necessary conceptions, tools and rules in accordance with a number of canons including the following:

1. All conceptions (from concepts to models) are developed, along with necessary tools and rules, and to the extent that is possible, in an experiential form. *Experiential knowledge* about a physical pattern is knowledge that one develops through interaction, or rather transaction in Dewey's sense,

with empirical data about the pattern in question. This is in contrast with *traded knowledge* that one learns about, mostly at face value, from other people, from textbooks or any other medium of information dissemination.

2. Every conception, tool or rule is developed *on a need basis*. A new model is introduced, as we shall see in § 6, only after students realize the limitations of a previous model(s) and are confronted with a new pattern that cannot be represented by any model already developed. The same goes for subordinate conceptions (concepts, laws and other theoretical statements). Any such conception is introduced only when needed for the construction or deployment of a given model. No conception, tool or rule is ever introduced for its own sake, otherwise students would see no interest in developing it and they would fail to consolidate it with the rest of their knowledge. This would subsequently impede their understanding of the new notion as well as of the model(s) that make(s) use of it.

3. Every conception is developed *progressively* within the context of the model (or set of models) that it serves for, especially when the conception is as involved as a law. For example, students progressively develop an understanding of the functional relationship expressed in Newton's second law before they come up with the corresponding formal statement. They do so by exploring physical situations pertaining to the free particle model and others pertaining to the uniformly accelerated particle model so that they gradually develop the law from a nominal expression to its formal expression as shown in Figure 5. As such, students: (a) overcome the paradigmatic barrier set forth by the mistaken belief that a force is required for an object to change its position, and (b) meaningfully develop semantic and syntactic aspects of the functional relationship that the law expresses.

4. All tools are developed along with associated *semantics and syntax*. No tool is used in modeling instruction under the assumption that students know how to use it, even when the tool is supposed to be fully developed in other courses. Semantic rules establish the correspondence between the tool being used on the one hand, and the empirical world and other representational tools, on the other. They set the norms for interpreting various elements of the tool or whatever product that the tool may bring about when used, and this both in the empirical and rational worlds. Syntactic rules spell out the conditions and guidelines for relating various elements of the tool to one another and to those of other tools, and for manipulating the tool in specific empirical and rational contexts.

5. No tool is ever localized or trivialized unless students discover that either is the case when the tool is put to the test under a variety of contexts. Students are encouraged to consider whatever tool used by scientists, irrespective of the discipline into which the tool was originally developed, or of the time at which its development took place. A tool commonly used in one scientific discipline may be considered for use in other disciplines. Some long forgotten tool may be reinstated; such tools are sometimes more efficient than ones that are nowadays being adopted and even revered.

1. *Nominal expression*: An object needs to interact with some agent(s) to change its velocity (in direction or magnitude), and not its position, in a given reference system. In the absence of any interaction, the object maintains a constant velocity in any inertial reference system.
2. *Ordinal expression*: When an object interacts with an agent that exerts a given force on the object, the velocity (or linear momentum) of the object changes in the direction of the force. The bigger the change of the object velocity in a given time (acceleration) for a particular mass of the object, or the bigger the mass of the object for a particular change in its velocity in a given time, the bigger the required force.
3. *Proportional expression*: Under the condition above, the required force is proportional to the object acceleration and mass.
4. *Formal expression*: Under the same condition, the required force vector **F** is equal to the product of the object acceleration vector **a** and mass m ($\mathbf{F} = m\mathbf{a}$).

Figure 5. Successive forms in which students progressively develop Newton's second law of dynamics.

5. Mediated learning

Students are guided to develop conceptions, tools and rules that are necessary for model construction and deployment in an *insightful* and *regulatory* manner. Teachers *mediate* the learning process. They provide students with guidance in timely manner so that students do not wander on their own in futile paths. They constantly induce students to reflect back on whatever knowledge that they might already possess and that relates to what they are learning in the classroom. Such reflection is rendered insightful in the sense that individual students become consciously aware of the limitations of their own conceptual structures or processes and of the sources of error when committed, and they explicitly realize what makes scientific realism superior to naïve realism from all perspectives. It is regulatory in the sense that individual students resolve any incommensurability between their own knowledge, on the one hand, and scientific theory and paradigm, on the other, and they proceed through a paradigmatic evolution that meaningfully tames down the naïve dimension of student profile in favor of the scientific (classic or modern) dimension.

In conventional instruction, students are normally conditioned to verbally reproduce theoretical statements and heuristics in situations typical of, if not identical to, the ones discussed in class. The whole learning experience is primarily about inscription of traded knowledge in student mind, mostly in short term memory, and seldom about formation of experiential knowledge. In the process, the student "learns about the real world from an intellectual distance, by reading about it", and is being filled "with information about the world, information that, in true written-word fashion, is removed from its context, at least to some extent, and represented rather than experienced directly" (Viau, 1994). Furthermore, students are seldom afforded the chance to go through a reflective experience whereby they could relate what they are told and shown in class to their own paradigms, and subsequently regulate, à la Dewey or à la Piaget, whatever "conflict" that might emerge in the process. As a consequence, students usually memorize by rote various theoretical statements and related problem solving routines with the only interest of passing course exams rather than learning something that could be personally relevant and meaningful. Their naïve realism remains entrenched in their minds, and they keep resorting to this realism in their everyday life and not to what they learned in class, thus ending up with a state of cognitive dissonance as noted in § 1 above.

Modeling instruction reverses the situation through insightful and regulatory reflection that involves, among others dialectics or "negotiation" modes shown in Figure 6. A student often needs to be engaged in all three negotiation modes across all dimensions of her/his paradigmatic profile (Fig. 1), but especially vis-à-vis the dimension or paradigm dominated by naïve realism. One of the three modes is an intrinsic rational negotiation, an assessment of *internal coherence* of a given naïve (or even common sense) paradigm. The other two are extrinsic negotiations. One involves an empirical assessment of *correspondence* of a student paradigm to physical realities. Another involves a rational assessment of *commensurability* between the student paradigm and the corresponding scientific paradigm. Depending on whether assessed paradigmatic components are originally viable (from a scientific perspective), naïve or missing, a negotiation of any type may result respectively in the reinforcement, modification or replacement of existing paradigmatic components, and/or the construction of new ones (Halloun, 1998b, in press). The outcome, in other words, consists either of the possible *transformation* of existing viable or naïve knowledge or the *formation* of missing one.

The outcome of a learning experience is determined primarily: (a) by the model being developed and corresponding epistemological and methodological requirements, and (b) by the initial state of students' paradigmatic profiles. It is then the teacher's responsibility to determine what sort of dialectics are most effective for those profiles to evolve and meaningfully incorporate the model of interest, and what sort of intervention or mediation is most appropriate to this end.

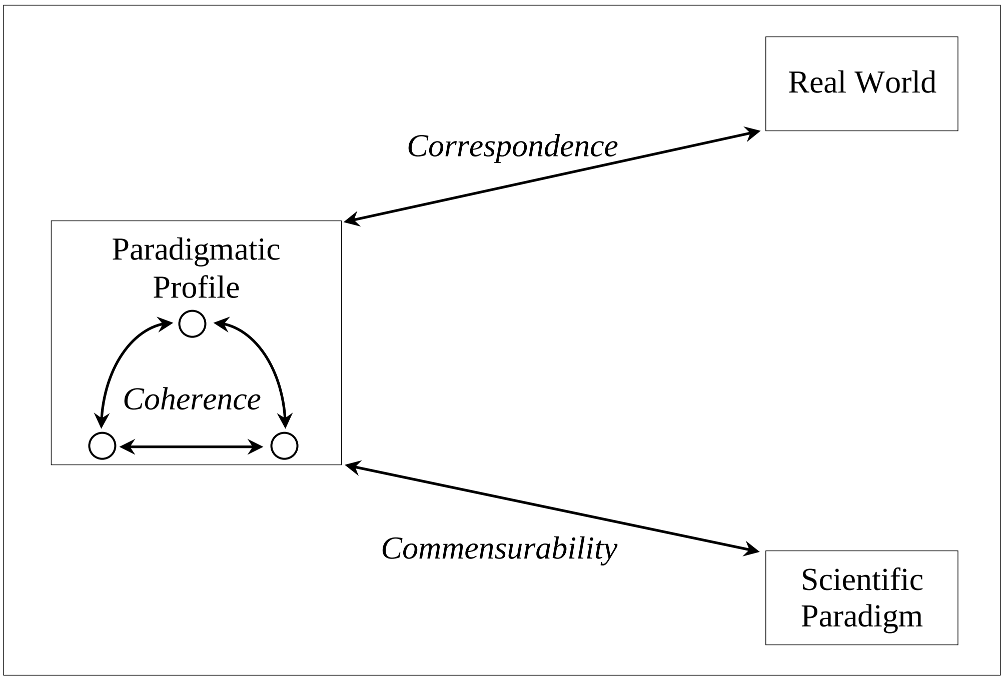

Figure 6. Rational-empirical dialectics for the evolution from the realm of naïve realism or common sense to the realm of science.

In an analysis of research published in the last two decades, Taconis, Fergusson-Hessler and Broekkamp (2001) found that teaching approaches that improve significantly student problem solving in science courses share the following three characteristics: (a) the deliberate intention "to enhance the quality of [students'] knowledge base", with a special "attention for schema construction", (b) "the availability of external guidelines and criteria…, i.e. objective [guidelines and criteria] provided by experimental set up or the teacher", and (c) "the presence of immediate feedback". The authors also found that "letting students work in small groups does not improve problem-solving education unless the group work is combined" with all three features just mentioned. Our modeling approach (Halloun, 1996; Halloun & Hestenes, 1987) came on top of the list of best practices identified by the authors. Taconis et al. (2001) had also noted that "a considerable part of the teaching experiments over the past 10 years has been devoted to aspects of learning tasks that are not effective, such as group work without immediate feedback or external guidelines and criteria", and that "treatments focused on the knowledge base have been given comparatively little interest". Many educators have come lately to recognize the shortcomings of modern educational trends that emphasize student-centered environments that are relatively free from all sorts of structuring. Even some constructivists have come lately to realize the need "to structure the environment in ways that would lead to a deeper understanding of science" and to recognize teachers' pivotal role in the process by admitting that "until each student respects the teacher and is willing to construct that person as his/her teacher, there is little point in proceeding with a curriculum that provides students with autonomy and opportunities to learn through inquiry" (Seiler, Tobin & Sokolic, 2001).

Modeling instruction is *student-centered* in the sense that it engages individual students actively in the learning process, but it does not leave them out entirely on their own free will. It has a specific agenda to fulfill: meaningful and insightful paradigmatic evolution within the confinements of a given curriculum, an agenda that cannot be fulfilled without teacher mediation. In fact, there is no meaningful learning without teaching, at least not for the overwhelming majority of students who cannot get self-educated. "We have centuries of evidence to show that natural thinking is neither rational nor scientific. Scientific thinking has to be cultivated and nurtured. It is the result of education… Without teachers there are neither scientists nor scientifically literate citizens" (Matthews, 2000, pp. 332, 349). Research has shown that even "gifted" or "genius" experts who out-perform their peers in arts and science owe their achievement to the fact that they benefit from "sustained and specialized intervention from skilled teachers and parents" and especially "master teachers who either themselves had reached that level or had previously trained other individuals to that level" (Ericsson & Charness, 1994). Teacher intervention is advocated, in modeling theory, not in the form of conventional lecture and demonstration, but in a sort of "mediated learning experience" whereby the teacher "mediates, transforms, reorders, organizes, groups, and frames" appropriate learning activities (Feuerstein & Jensen, 1980).

In modeling instruction, teacher mediation preserves a central role for student engagement and active participation in decision-making. Depending on the circumstance, mediation may take the form of moderation, arbitration or scaffolding, and it always involves *teacher feedback* so as to prevent students from going astray and to keep their reflective inquiry aligned as closely as possible with scientific inquiry. Moderation and arbitration are appropriate when students have their own ideas about topics of instruction. Scaffolding is most appropriate when students lack any knowledge about such topics, but it may also be resorted to in order to enhance moderation and arbitration.

As a *moderator*, the teacher solicits ideas about a particular topic, and then guides students to compare ideas and resolve possible incompatibilities to the extent that they can do it on their own. The teacher does not intervene directly in the process to resolve the matter in favor of one idea or another. S/he can only passively supply some rational or historical details, or some empirical data that may help students brainstorm, clarify to one another specific ideas of their own, or bypass a stalemate that they may get to. The teacher gets more involved in the mediation process as an *arbitrator*. This role is especially important when students have conceptions or follow rules of engagement that are incommensurable with science (naïve or of limited viability). The teacher would then bring concerned students first to a conscious state of *cognitive disequilibrium*, and direct them next to negotiate things with their colleagues so as to get them resolved in favor of a particular position that is viable from a scientific perspective. The teacher does so first by invoking among students a sort of Socratic dialogues (Hake, 1987, 1992). When this fails to bring things to a satisfactory closure in due time, the teacher shifts to scaffolding and offers the scientific position as an alternative that students are asked to ascertain.

Scaffolding is, for us, the type of mediation whereby the teacher gets most involved in directing the learning experience in the scientific direction. This sort of mediation is resorted to when arbitration fails to bring about students' self-regulation, but especially when students' knowledge about the topic of instruction is totally missing. In the latter event, the teacher intervenes by confronting students with empirical situations or data from which they are guided to infer the appropriate conception(s), and/or by helping students rationally derive such conceptions from prior knowledge. The teacher may provide students with appropriate tools in the process. When students fail to construct the target conception, or conduct a particular modeling process, in this manner, the teacher induces them to do so in a more direct way by presenting them with the scientific conception or process. The scientific position is though not imposed in an authoritative way, but it is offered only as an alternative that students are asked to consider and ascertain on their own in order to be convinced of its viability. The teacher does the same when arbitration fails to meet its ends. Students would subsequently be asked to deploy the scientific conception or process in a sequence of modeling activities where the teacher can gradually retreat from direct intervention, somewhat in the manner promoted in cognitive apprenticeship and similar modes of instruction (Heller, Foster & Heller, 1997; Shore et al., 1992; Roychoudhury & Roth, 1996). Scaffolding is especially needed at the beginning of a science course when students develop the most fundamental basic models (e.g., free particle and uniformly accelerated particle models in Newtonian theory). Subsequently, the teacher progressively moves away from this mediation form as students become more and more autonomous in model construction and deployment. The nature and the course of teacher mediation are in fact primarily governed by the stage at which students are in a given learning cycle.

6. Learning cycles

The content of a science course is subdivided in accordance with modeling theory into units each devoted to the development of a particular model. Students develop a model and its requirements in a well-structured learning cycle. The idea of a learning cycle as a *structured*, *mediated* form of learning, was first proposed by Karplus (1977), primarily for teaching concepts of elementary school science within the framework of Piaget's theory of intellectual development. Karplus "learning cycle consists of three instructional phases that combine experience with social transmission and encourage self-regulation… These three phases are exploration, concept introduction, and concept application". In the first phase, students are invited to explore an unfamiliar empirical situation in ways that "raise questions or complexities that they cannot resolve with their accustomed patterns of reasoning… As a result, mental disequilibrium will occur and the students will be ready for self-regulation". A new concept or principle is introduced in the second phase to resolve the problem at hand, and then applied in the third phase where "familiarization takes place as students apply the new concept and/or reasoning pattern to additional situations". Social transmission (i.e., teacher lecture for transfer of traded knowledge) is reduced in the first stage. It reaches its peak in the second phase where teachers reclaim their conventional role of lecture and demonstration, and it winds down in the third phase where "physical experience with materials and social interactions with teacher and peers play a role" (Karplus, 1977).

In our modeling theory (Halloun, in press), we have drawn on Karplus idea, as well as on practices in science education that have gone successfully in line with his learning cycle. We subsequently designed (and successfully tested) our own learning cycle so as to promote the paradigmatic evolution we aim at in the most effective and efficient way possible. A modeling

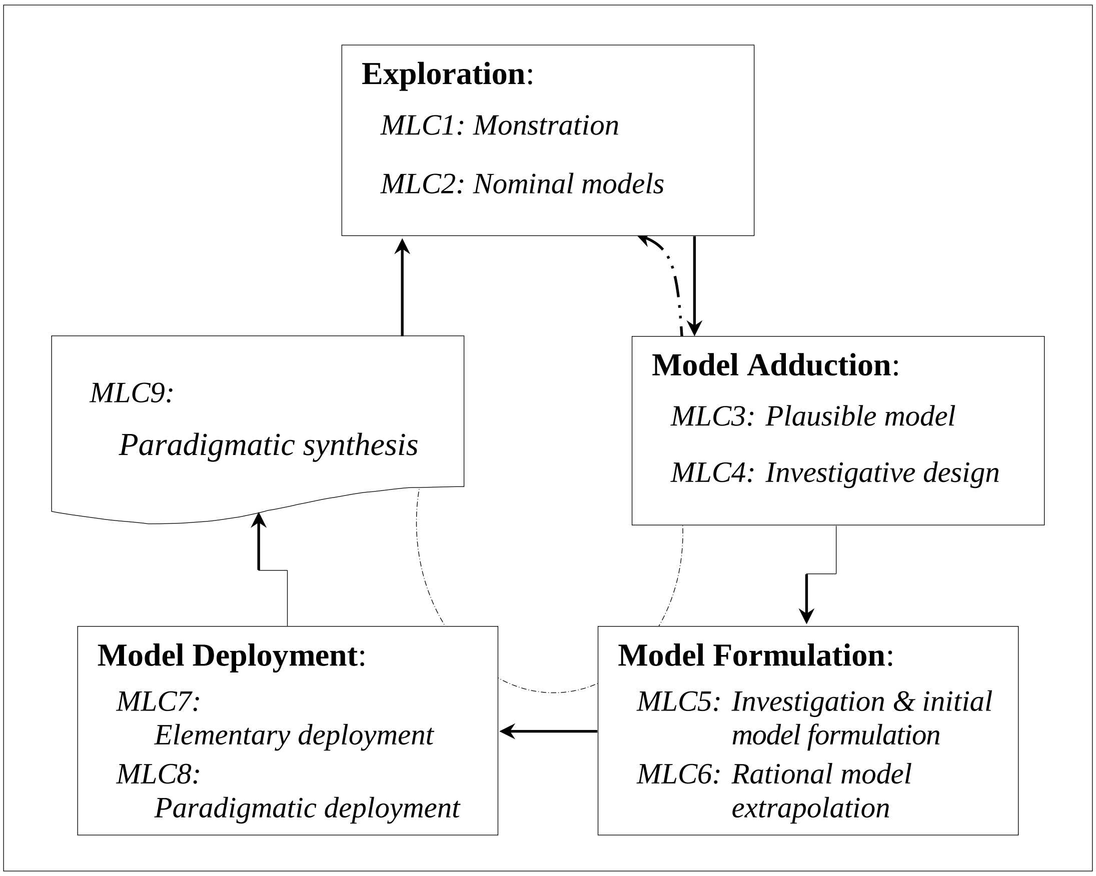

Figure 7. Modeling learning cycle.

The dashed, curved arrow indicates that one may go back to any preceding phase as a result of rational and empirical *evaluation* that takes place continuously throughout the cycle.

learning cycle (MLC) of ours is a five-phase cycle. Successive phases are those of exploration, model adduction, model formulation, model deployment, and paradigmatic synthesis (Figure 7).

A modeling learning cycle begins with the *exploration* phase. This is a two-stage phase (monstration and nominal models proposition) devoted to first motivate students to embark on the construction of a new model of well-defined scope and then roughly consider possible candidates in this direction. In the monstration stage (MLC1 in Fig. 7), students are brought to a state of cognitive disequilibrium whereby they realize: (a) the inadequacy of prior viable knowledge (already constructed models, if any) for describing, explaining and/or predicting in some respects a new pattern that is outside the scope of prior knowledge, and thus (b) the necessity to construct a new model in order to come up with the correct inferences about the pattern in question. Construction of the target model begins in the second stage of the cycle (MLC2) with rough subsidiary models. Subsequently, and throughout the cycle, students are brought closer and closer to the target scientific model through progressive refinement or approximations.

A model is *progressively* developed through a given cycle. When students possess alternative conceptions of limited viability, modeling activities begin with these conceptions and proceed to get them gradually refined until they become commensurable with scientific theory. In this respect, the construction of a given model may begin with a *subsidiary model* that corresponds to the target model, and that students might be familiar with from everyday life and/or from other courses. Otherwise, students begin the process with the construction of a new subsidiary model. Various schematic dimensions of the subsidiary model are then gradually refined and built up until the model acquires the desired form. This is how, for example, construction of the uniformly accelerated particle model may begin with the subsidiary model of a particle in free-fall. At some levels, *successive refinements* of the subsidiary model or of any student conception of limited viability may follow the approach prescribed by Barbara White in her ThinkerTools. White (1993) developed a software whereby, among others, students develop the concept of constant force through a hierarchy of simulation activities, beginning with an activity that simulates the force with identical pulses imparted to a dot on a computer screen.

A *nominal model* constructed in the second exploration stage (MLC2) is a generalization of a subsidiary model. As noted above, a subsidiary model is originally mapped on a particular instance of a pattern, a particular system or phenomenon that students are familiar with, whereas the emerging nominal model is about the pattern itself, i.e. about all physical realities exhibiting the pattern. Both subsidiary and nominal models are entirely constructed by students, and the underlying student paradigms may be anywhere in the profile spectrum extending from naïve to scientific. The structure of the subsidiary model may be well developed in student minds. However, students are intentionally guided to generalize the particular structure of this model in a nominal form (Fig. 5) at this stage in order to ensure that peer negotiations and self-regulation in the coming stage be headed in the right direction, and reduce the chances of coming back to refine model composition in subsequent stages.

Students negotiate subsidiary and nominal models among themselves under teacher moderation. As a moderator, the teacher brings students together to discuss their own models among themselves and practically refine them on their own. S/he could intervene when students fail to do so on their own, but with the only purpose of clearing the way of student negotiations from any noise. This may involve clarification of some student views to the rest of the class, reminding students of conceptions they ask about, passive supply of some empirical data, historical cases or any information that may help students brainstorm and bring their naïve ideas to the surface or get out of any possible gridlock in their negotiations. By the end of this stage, students eliminate all models they duly consider non plausible so that they would be left with no more than three candidate (nominal) models for consideration in the coming stage.

The exploration phase is followed by the *adduction* phase that is intended to focus students' attention on one plausible model that appears to be reliably mapped on the new pattern that is being investigated in the cycle. This is also a two-stage phase. The first stage (MLC3 in Fig. 7) is devoted to the proposition of a *plausible model*, and the second stage (MLC4), to the proposition of an appropriate *investigative design* for empirically testing this model. By the end of this phase, students resolve major incommensurability between their own models and the target scientific model while enhancing their methodology of inquiry. As a consequence, they significantly reduce the naïve dimension and build up the scientific dimension of the corresponding profile (Fig. 1).

In MLC3, students compare nominal models they proposed in the previous phase in a way to come to a consensus on a single model. The emerging model bears all viable elements of its predecessors. It is a hypothetical model that students conjecture explicitly according to the model schema. Nominal hypotheses conjectured in the exploration phase are gradually converted into ordinal hypotheses, and then, if possible, into ratio-type hypotheses (Fig. 5). The plausible model may still include some residual secondary (non salient) and/or naïve elements that students could not entirely resolve, residues shared by all or some groups of students. These residues will be cleared out in the next phase.

In MLC4, students propose and negotiate ideas leading to an investigation designed to assess the model so that it be ready for refinement in the following phase. Depending on equipment availability and procedural feasibility, the design can pertain to a classroom or field experiment, to observations in the real world, or to empirical data about the pattern of study provided by teacher or any other reliable source.

The teacher whose role was restricted to moderation of student brainstorming and negotiation in the previous phase assumes now a more active role, an arbitration role. As an arbitrator, in MLC3 the teacher intentionally steers student interaction in the direction of a single candidate model that is proposed in accordance with the model schema and that has a relatively high degree of viability and low degree of naïveté by comparison to its subsidiary and nominal predecessors. If necessary, s/he also ensures that appropriate new conceptions be constructed to this end. In MLC4, the teacher makes certain that students come up with a sound investigative design to assess the tentative model along with necessary norms and criteria for model acceptance and refutation.

Efficacy and efficiency of a learning cycle depend mostly on the prior two phases, and especially on the model adduction phase. The more of their own ideas they expose in these two phases and assess in class by comparison to one another, and the more transparent and focused the investigative design gets in their minds, the better the chances are for students to bring the self-regulation process to a meaningful conclusion at this point and progress in the direction of a truly scientific model. Gradual formulation of this model takes place for the most part in the third MLC phase, and is achieved in the last phase following model deployment.

The third phase of the modeling cycle is the *formulation* phase. This also a two-stage phase devoted to the formulation of a comprehensive and scientifically sound model based on the outcomes of the investigative design of MLC4 that students carry out in this phase. The formulation will not be exhaustive though because the model has not been sufficiently deployed yet. Model deployment takes place in the fourth MLC phase. New insights will subsequently be gained into various aspects of the model, and the model will be brought then to a maturity level that is high enough to conclude the learning cycle.

In the first formulation stage (MLC5 in Fig. 7), students conduct, in collaborative groups, the investigation they designed in the previous stage, and refine the plausible model of MLC3 in light of the investigation outcomes. By the end of MLC5, students achieve a *preliminary formulation* of the target model, a viable but incomplete formulation. The model thus formulated is a refined, formalized form of the plausible model conjectured in MLC3. Hypotheses in the latter are corroborated, modified or replaced, and the originally conjectured relationships are more precisely expressed (e.g., ordinal or proportional hypotheses are turned into ratio-type law statements). Seldom new major elements that have not been thought about before in one form or another emerge in the newly refined model. There is virtually a one-on-one mapping between this model and its predecessor. It is thus common that some primary features of the target model may still be missing. Aside from issues that may be brought about only after model deployment, student investigations cannot possibly cover all model aspects at this stage. Furthermore, various constraints may make it impossible for students to empirically corroborate or even induce certain model aspects. Such aspects may then only be inferred by rational analysis and extrapolation, and perhaps only through teacher scaffolding. These aspects make the object of the next stage.

In the second formulation stage (MLC6), the model constructed so far gets rationally analyzed and extrapolated so as to come close to a comprehensive model formulation. *Rational extrapolation* can take place within the model in question, and/or from previously constructed models. For instance, by the time they have achieved MLC5, students would have already refined, in the form of scientific laws, all hypotheses conjectured in MLC3. When these laws are insufficient to complete the model structure, students can be guided to induce missing laws from available data if possible. If not, they can be guided to formulate these laws by rational extrapolation of laws they have already formulated in MLC5, and/or laws formulated in previous learning cycles, be it generic laws or laws that are particular to some old models.

The teacher assumes consecutively two different roles in this phase of the learning cycle. At the beginning of MLC5, and all through the actual investigation process, the teacher retracts from the arbitration role to supervise the process from a distance as a moderator. Once the investigation is completed and students have prepared their reports, the teacher gets again more involved as an arbitrator of students' interaction to ensure that the model is properly formulated in MLC6. Sometimes, the teacher may even find it necessary to step up her/his intervention to take the form of scaffolding. As such, the teacher may instruct students to follow explicitly a specific path and/or provide them with necessary concepts and tools that are totally missing from their paradigmatic profiles and that are indispensable to complete model composition and structure. Scaffolding may take the form of lecture when practical constraints prevent students from coming up with any of these concepts and tools on their own.

A model gains its full significance only after deployed in the real world for describing, explaining, predicting and controlling the structure and/or behavior of a variety of existing physical realities, for inventing new conceptual or physical realities, and for subsequently bringing to new horizons the theory and paradigm which the model belongs to. New insights are gained as the model is deployed in different contexts and envisaged from different perspectives. It gradually gains in scope (domain and function), and it gets better and better situated in the corresponding theory.

The model constructed up to the third phase of a modeling cycle is deployed in the fourth phase. *Model deployment* activities are chosen so as to allow students complete and reinforce all four schematic dimensions of a model (especially issues that may still be pending at this point), and promote model-based inference in various empirical and rational contexts. Activities are conducted following systematic schemes that students develop for adducing the appropriate model(s) to the "givens" in a situation, and not following rules of thumb or context-specific prescribed routines to determine convenient "relationship(s)" between givens and unknowns. Such schemes and required tools and skills are progressively developed in two deployment stages. In the first stage (MLC7), students deploy in each activity only parts of the model formulated in MLC6. Deployment situations get progressively more complicated until they reach the level of *paradigmatic situations* in MLC7 (Halloun, 1998b), situations each of which requires deployment of the model structure in virtually its integrity. Activities in both stages are chosen to cover all four deployment categories distinguished in Table 1 (application, analogy, reification, and extrapolation), and they are not limited to conventional paper-and-pencil exercises and problems. They include, in addition to conventional exploratory activities, investigative activities of all sorts, thought experiments, historical and contemporary case studies of interdisciplinary nature.

Deployment activities, and especially those of paradigmatic deployment, are conducted under teacher arbitration following the same guidelines as the previous two stages. Students are encouraged more in this stage than ever before to rely on themselves and collaborate with the members of their groups whenever possible, and to carry out every deployment activity while reflecting on their own knowledge and regulating it in the most insightful way possible. To this end, they conduct every deployment activity in the manner they conducted the investigation of MLC4 and MLC5, individually or in groups, during class hours whenever that is possible. They expose their work afterwards and discuss it in class the same way they did in MLC5. When peer negotiations head to a dead-end after all possible arbitration, and only then, the teacher may intervene to resolve the issue one way or another by scaffolding.

A learning cycle and thus a modeling unit of instruction are not brought to closure with deployment activities. New insights are gained about the model under construction in the deployment phase. Students need then to consolidate their experience in this phase with what they achieved in previous phases. The last stage of the learning cycle (MLC9 in Fig. 7) is devoted to this end and to subsequent recapitulation of the paradigmatic evolution students gradually achieved in the cycle. Consolidation and recapitulation are conducted as critically as any other process undertaken during the cycle. Every point is systematically evaluated in this stage like in any other stage, and this along the lines of Figure 6. If determined to be viable, students proceed to the following point. Otherwise, students go back to a previous stage where the source of the problem might be rooted so that they can reconsider things and refine them appropriately. The process continues under teacher arbitration until students complete the synthesis of the current cycle and set the stage for the following cycle. Such an evaluation is in fact not limited to this stage, but it is carried out throughout an entire cycle, as implied in the dashed, counterclockwise arrow of Figure 7.

7. Efficacy of modeling instruction

Development of modeling theory has gone in the last two decades with this author (and is still going) through cycles similar to the modeling cycle described above. The theory that has repeatedly shown to be efficacious for secondary school and college physics courses is now being progressively deployed in various scientific disciplines and at all educational levels. Early outcomes show that modeling theory is at least as promising in the latter respects as it is for physics education.

Normative evaluation of modeling theory is the object of a companion paper presented at this SAARMSTE conference (Halloun, 2004). Procedures and outcomes showing the relative efficacy of various components of the theory in fostering the paradigmatic evolution advocated for in this paper are presented in the companion paper. All in all, when deployed in secondary school and college physics courses, the theory has been leading to the following outcomes:

- *Better conceptions*. Students show significantly better conceptual understanding of scientific theory following modeling instruction than following other forms of instruction. The Inventories of Basic Conceptions (IBC) is a battery of standardized instruments developed by this author for assessing student qualitative, conceptual understanding of basic conceptions (concepts, laws) in given courses. IBCs include instruments similar to what used to be called the Mechanics Diagnostic Test (Halloun, 1984; Halloun & Hestenes, 1985b) or the Force Concept Inventory (Hestenes, Wells & Swackhamer, 1992) in physics education. Under modeling instruction students score on IBC posttests up to two standard deviations, on average, higher than students who learn physics under conventional instruction of lecture and demonstration.

- *Better processes*. When given identical assignments and exams consisting of tasks similar to end of chapter problems typically found in traditional textbooks, students score on average up to three times better under modeling instruction than under conventional instruction. The better performance is reflected in systematic problem solving (modeling) procedures used significantly more by the former group of students than the latter.

- *Better views about the nature of science*. The Views About Science Survey or VASS (Halloun, 2001b, Halloun & Hestenes, 1998), is a battery of instruments designed to assess student views about the nature of scientific theory and about how scientists go about developing and validating such theory. As assessed by VASS, more students express views about the nature of science aligned with scientific realism rather than naïve realism following modeling instruction than other forms of instruction.

- *Better learning styles*. VASS also includes parts designed to assess how students go about studying a given science course. It shows that students under modeling instruction tend to follow the canons of reflective and insightful inquiry more systematically in their study than other students.

- *Lower attrition rates*. The rate of students who withdraw from a given course before its end or fail the course upon its completion is in modeling down to one third of what it normally is in conventional courses.

- *Equitable learning*. May be the most significant outcome of modeling instruction is that it bridges the gap in a way yet unmatched between students who are traditionally considered as low achievers and those who are considered as high achievers. So-called low achievers are normally left behind following conventional instruction. Instead, under modeling instruction, they are enabled to complete their courses with above average performance.

- *Transportability to other courses*. Inquiry skills, tools and learning styles that students develop under modeling instruction are stable and generic. Students take advantage of them to excel in their study when taking subsequent science courses, irrespective of whether or not modeling instruction is followed in these courses.

Acknowledgments

The first six sections of this paper draw on an upcoming book for the author on modeling theory in science education (Halloun, in press). The last section draws on a companion paper presented at this SAARMSTE conference and dealing with the evaluation of modeling theory (Halloun, 2004).

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