Model-laden inquiry for effective physics instruction

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Abstract

Physics students often fail to transcend the realm of common sense and evolve into the realm of science following conventional instruction of lecture and demonstration. In contrast, practice shows that this evolution can be made possible through model-based, reflective inquiry. In such a process, students are empowered with scientific tools and habits to reconstruct every physics theory around a few basic models. The most important of these tools are modeling schemata which students use to conceptualize and organize their knowledge meaningfully, and use it efficiently, in the context of real world, everyday life situations. Students develop all tools and habits needed for scientific inquiry in four-stage learning cycles (exploration, invention, formulation, exploitation). Each cycle is devoted for the development of a specific model. All along a cycle, individual students ascertain their ideas in light of empirical and rational evidence at their disposal, and negotiate these ideas with their peers, in order to self-regulate any incommensurability with physics that might emerge in the process.

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Arts and sports are never taught by lecture and demonstration, and they should not. Due training is always given in hands-on workshops and in practice courts, respectively, where apprentices are equipped with suitable tools. Science is at least as involved as arts and sports (if not more, especially with regard to the latter), inherently and cognitively. Yet tradition awkwardly had it that science courses be taught by lecture and demonstration, following rules of thumb, and with inefficient tools, if any. When students fail to "get" the right message, and they often do, we blame them for not being devoted or even talented enough. Instead, we should blame our traditional teaching practice and turn to more authentic approaches following the example of arts and physical education.

Modeling theory is an educational theory that we have been developing for the last two decades within the context of physics in order to offset the shortcomings of conventional instruction by lecture and demonstration, and provide students with an opportunity for meaningful learning of science. The theory maintains that scientific inquiry is model-based, and that meaningful cognitive development takes place through reflective thinking and self-regulation. Accordingly, it calls for a learning environment that is structured enough to allow high school and college students transcend the realm of common sense, and evolve into the realm of science through model-based, reflective inquiry (Halloun, 2000).

In this article, we first outline the nature of the targeted evolution, and we discuss afterwards how conventional physics instruction makes students fall short of it. We then present an overview of the modeling theory, and we follow by showing how the content of physics courses and learning processes can be structured accordingly in order to allow students evolve meaningfully into the realm of science. We last survey some strengths of the theory that have been revealed so far by practice.

Paradigmatic evolution

A person's thought and behavior in a given situation are always governed by a particular paradigm (Kuhn, 1970). We call *paradigm* an intellectual system that sets the conditions of an act, be it mental or physical, and that establishes standards and rules that govern the choice and the course of all actions necessary for the reification and continuous evaluation of the act in question (Halloun, 2000). Due to biological and cultural differences, the paradigm involved in a given situation may vary from one person to another. Paradigmatic differences are more pronounced among ordinary people than among the members of a community whose specialty covers the situation in question. In fact, when it comes to science, differences among concerned scientists are so insignificant that we can say that they all share the same paradigm*, a paradigm that transcends ordinary people's common sense.

Science education should thus engage students of all levels in a *paradigmatic evolution* that enhances, in reasonable and feasible ways, student state in the following respects:

* A scientific paradigm may be defined along four dimensions. The first is an ontological dimension; it includes a set of generic postulates about the reality of physical systems and events in the universe. The second is an epistemological dimension; it consists of a set of scientific theories along with conceptual tools necessary for their construction. The third is a methodological dimension; it involves habits, procedures and rules of inquiry. The last dimension is an axiological dimension; it embraces attitudes and values that govern the evaluation of the validity, utility and repercussions of scientific theory.

- Personal views about the reality of things in the universe and their relation to a cognizant person.
- Necessary aptitudes and attitudes for establishing objective and precise knowledge about the real world.
- Conceptual tools and procedures for inquiring about the real world and interacting with it efficiently and meaningfully.
- Templates for organizing personal knowledge and mnemonics for retrieving it in an optimal way.
- Standards, rules and criteria for evaluating personal knowledge and action.
- Efficient study habits.

Conventional instruction: Myths, pitfalls and shortcomings

High school and college students often start their science courses with common sense paradigms that are incommensurable, and sometimes at odd, with scientific paradigms. The situation is especially alarming in the case of physics (diSessa, 1993; Halloun, 1986; Halloun & Hestenes, 1985 & 1998; Hammer, 1994; Minstrell, 1992). Except for those who can do without the teacher, practically no student can attain the advocated paradigmatic evolution following conventional instruction of show and tell. In fact, educational research has been constantly showing that a good proportion of high school and college students experiences the following drawbacks:

- Wrong views about the nature of science in general, and physics in particular, and its relation to the real world and everyday life.
- Negative attitudes toward physics.
- Tenacious situation-specific, vague, mutually confused, fragmented, loose, and incoherent common sense ideas about physical systems and phenomena.
- Learning by rote, with a concentration on the memorization of mathematical formulas and routines, and through blind imitation of authority, be it the teacher or the textbook.
- Formula-based, trial and error problem solving tactics.
- Fast decay of accumulated knowledge.
- Gap widening between low and high competence students who virtually preserve the same ranking throughout the year.

Teachers and students of all levels often conceive science education as a process of information transfer whereby students accumulate passively whatever fact is conveyed to them by an instructor or by a textbook. This process is inherently unproductive, especially in physics, and its purpose is further defeated by the wrong assumption that students are originally motivated and equally ready to learn transferred knowledge meaningfully.

In fact, students seldom realize the relevance of physics to their personal life, and they often take physics more to satisfy what they believe are unworthy curriculum requirements than for personal benefit. The only motivation they are thus left with is to pass their exams, and they often succeed in this task after simply memorizing by rote a bunch of formulas and routines for solving textbook problems. Students' apparent success is thus deceiving; by no means it reflects their actual understanding of what physics is all about (cf. references above).

The situation is worse with the other side of the coin, student readiness to learn physics meaningfully. Many physics students at all levels lack necessary tools to assimilate transferred material on their own, and a good sum is often encumbered with common sense beliefs about physical systems and phenomena that are incommensurable with scientific theory. The incommensurability is at times so acute (high conflict in the Piagetian sense) that it impedes students from acquiring scientific knowledge.

Major tools students lack include those needed to: (a) interpret textbook readings and teacher discourse, and discern relevant information there, (b) conceptualize and organize selected information appropriately, (c) develop and implement rules of inquiry and problem solving, and (d) detect and resolve flaws in one's own knowledge. To add insult to injury, it is often assumed that students can develop these tools simply by watching teacher performance in the classroom, and that they can subsequently do without guidance in their study. Students are thus left to wander in dark labyrinths!

Modeling theory and paradigmatic evolution

Educators have been trying in the last two decades to redress the deficient state of physics education. Their efforts have gone basically in three directions. Some, like diSessa (1993) and Minstrell (1992), have concentrated on identifying and treating cognitive underpinnings of student common sense knowledge. Others have tried to help students organize their knowledge in specific ways (Fisher, 1990; Goldberg, Bendall & Bach, 1991; Novak, 1990; Novak, Gowin & Johansen, 1983), and/or develop particular prescriptions for solving physics problems (Eylon & Reif, 1984; Larkin & Reif, 1979; Reif & Allen, 1992; Reif & Heller, 1982). In parallel, many educators have focused on teachers' practice and student learning habits. Some of these educators, like Karplus (1977), have called for engaging students actively in structured learning strategies, while others, especially constructivists, have appealed for giving up lecture and demonstration in the classroom altogether, and letting students build on what they already know, on their own, and with little guidance, if any (von Glasersfeld, 1989a, 1989b, 1993; Driver et al., 1985, 1986, 1989; Tobin, 1993).

All these new trends have had limited success in practice so far, either because they have focused on a specific pedagogical dimension among many, or because they would call for some unrealistic or dubious approach (like in the case of so-called radical constructivists). Our position has been all along that as much as it is unlikely for the paradigmatic evolution discussed above to take place under conventional instruction, it is at least as much so by letting students construct knowledge on their own. Effective physics instruction is, for us, somewhere within all trends outlined above and beyond. It is one that creates a learning environment that is structured enough to allow students construct their own knowledge within the guidelines of scientific epistemology and methodology, and following clear rules of engagement with others and with empirical and rational evidence.

In this spirit, we have been working in the last two decades on the development of *modeling theory* for high school and college science (and mathematics) instruction. The theory is grounded in cognitive and educational research as well as in the philosophy of science. It has been validated so far within the context of physics in the manner described in the last section of this article. It basically calls for learning science through model-based, reflective inquiry, and is distinguished by the following aspects (Halloun, 2000):

- It has explicitly stated philosophical principles about scientific enterprise and cognitive principles about student knowledge development. These principles converge partially with modern philosophical and cognitive schools without being stamped with any particular school.
- It sets clear instructional goals along the lines of the paradigmatic evolution discussed

above. A major goal being to help students develop learning tools and habits that they commonly miss under conventional instruction.

- It calls for a learning environment that is structured enough to allow students to construct their own knowledge within the guidelines of scientific epistemology and methodology. A special attention is given in this direction to modeling processes and organizational templates that scientists commonly use, often implicitly, to organize their theories around basic models.
- It is student-centered in the sense that individual students are guided, through structured learning cycles, to construct new knowledge while constantly ascertaining their own ideas in light of empirical and rational evidence at their disposal, and to negotiate these ideas with their peers dialectically, in order to self-regulate any incommensurability with physics that might emerge in the process.

In the following, we limit our discussion to practical issues pertaining primarily to the last two points.

Modeling schemata for structured knowledge

In our modeling theory, we maintain that every scientific theory can be coherently organized around a few basic conceptual models, and that, when adequately articulated, these models allow students to organize their own knowledge meaningfully and employ it efficiently in all sorts of inquiry and problem solving. A *scientific model* is a conceptual system that allows us: (a) to describe, explain, predict, and control, in some respects and to a certain degree of approximation, a specific *pattern* in the structure and/or behavior of a set of physical systems, and, eventually (b) to invent new systems or phenomena. A *basic model* is one that is simple enough to facilitate student understanding of fundamental tenets, laws and concepts of the respective theory, but generic enough to serve in the construction of more complex models in the theory.

For example, Newtonian theory of mechanics is meant to study physical objects that undergo translational motion in inertial reference frames, with relatively small speeds (by comparison to the speed of light), and without being significantly affected by their geometric properties of shape and dimensions. Consequently, the theory in question consists of *particle models*, i.e. models of dimensionless objects, the most fundamental of which are the basic particle models shown in Figure 1.

Figure 1

A physics course consists traditionally of a series of chapters bearing on specific concepts and laws in a given theory. One concept or law is presented after another, episodically, without a global view that reflects the coherence of scientific theory. Such coherence is best displayed in models. Yet, we rarely see traditional textbooks even mentioning the word “model” in their discussion, and if they do, they misuse the term to denote a prototype of some sort, an equation, or a specific pictorial or graphical representation. In contrast, in our modeling theory, we maintain that models and modeling processes should be at the center of physics instruction, and that the content of a physics course should be divided primarily into chapters bearing each on a specific basic model of the sort presented in Figure 1.

Physics instruction should then primarily help students develop appropriate tools for constructing and employing basic models in the context of conveniently chosen real world situations, and eventually through rational (abstract) exploration of conceptual knowledge. The most important of these tools are organizational templates that we call *modeling schemata*, and the two most indispensable schemata for high school and college students are the model schema and the concept schema.

Model schema is a four-dimensional template that one can use to construct any scientific model. As shown in Figure 2, two dimensions, composition and structure, define a given model, and two others, domain and organization, situate the model in a given theory. The four dimensions allow one to construct what is often referred to in the literature as *declarative knowledge* about a model. It is complemented by some *procedural knowledge* (partly discussed in the next section), i.e. by a set of rules provided by the theory that contains the model for guiding its construction and employment (Halloun, 1996a & 2000).

Figure 2

Students may be guided to develop such a schema in the classroom, and use it consequently in the construction of all models in a given physics course, by systematically asking themselves and answering specific questions like the following:

Domain:

- 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?

Composition:

- What conceptual objects does the model consist of?
- What agents in the respective environment interact with these objects?
- In what kind of coordinate system can these objects and agents be most conveniently studied?
- What intrinsic descriptors (i.e., 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?

Structure:

- What descriptive and/or explanatory function does the model serve?
  (e.g., a kinematical or a dynamical model)
- What geometric structure does it have?
  (e.g., none for particle models in Figure 1, topography of many-particle models)

- 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 state laws describe best the behavior of each object?
  (e.g., so-called kinematical equations of motion, like r(t))
- 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?

Organization:

- What are the limitations of the model?
- What features does it share with other models in the theory to which it belongs?
- 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?

Different types of concepts enter into the composition of a model, the most important of which in physics are object concepts (e.g. the particle as a dimensionless object), property concepts or descriptors (e.g., mass, position, force), and logico-mathematical operators. Concepts, and especially descriptors, gain their significance only when used in model construction. The same is true for laws, definitions and other conceptions. A model is to a concept what an atom is to an elementary particle. An atom is composed of elementary particles, but a single elementary particle has no bearing to the structure of matter without its interaction with other particles to form atomic structures with emergent properties distinguished from, and in some respects more important than, individual particle properties.

In order to build concepts comprehensively and integrate them coherently into respective models and theory, we complement the model schema with a *concept schema*. As shown in Figure 3, the latter is a five dimensional template used for the construction and employment of individual concepts within the context of basic models (Halloun, 1998a & 2000). Like in the case of the model schema, students conceive the concept schema in the form of a set of questions that they need to answer systematically, while constructing and employing any concept, in the framework of a given model or family of models.

Figure 3

Modeling schemata offer suitable tools for instructors to plan instruction and to evaluate student learning and teaching practice, and convenient templates for authors to design their textbooks. Teachers, and textbook authors alike, can follow these schemata to ensure that all relevant aspects of a conception are covered appropriately, whether during the course of instruction or, afterwards, in various forms of follow-up assignment and assessment. In the latter respect, modeling schemata serve as major frameworks for building a valid and reliable taxonomy of declarative and procedural knowledge that need to be practiced and assessed. The taxonomy must then be deployed in various authentic ways, and not only in conventional paper-and-pencil problem solving tasks, in order to find out whether students have actually reached meaningful understanding of the covered material. Assessment results would consequently enable teachers choose appropriate activities that can help students detect and resolve flaws in their own knowledge, and evolve into the realm of science in the manner described in the next section.

Modeling cycle for structured reflective inquiry

For the paradigmatic evolution to take place efficiently, we hold, in our modeling theory, that science instruction must conform as much as possible to the rules of scientific inquiry while allowing individual students to self-regulate any incommensurability between their own knowledge and scientific paradigm. In this direction, we engage students in well-structured learning cycles whereby they construct and employ one model after another following the modeling schemata discussed above.

In a modeling learning cycle (MLC), students proceed in four consecutive stages for constructing a new model and using it in real world situations (Figure 4). The stages are called consecutively: exploration, invention, formulation and exploitation (in the good, advantageous sense of the word). Each stage consists of two or three major steps (discussed below). A modeling cycle is helicoïdal: one may proceed to a given step only after completing the prior one; however one may return to a preceding step to fill some detected gaps, if any. Once the last step is completed (MLC10 in Figure 4), students begin a new cycle for constructing a new model.

Figure 4

Students proceed dialectically along a cycle in order to self-regulate their own paradigmatic state (Halloun, 2000). They constantly evaluate their own knowledge in light of empirical and rational evidence put at their disposal (Figure 5), and they regularly negotiate their ideas with their peers under the supervision of the instructor. Sometimes, and especially when student ideas are somewhat valid and need minor refinement, the self-regulation process succeeds following either one of two levels of dialectics, or both. The first level pertains to an *intrinsic rational dialectic* whereby students evaluate the *coherence* of their own ideas without any reference to new outside evidence. The second level pertains to an *empirical-rational dialectic* whereby students need to assess the *correspondence* of their ideas to empirical evidence in real world situations. Sometimes, and especially when student ideas are completely at odd with a scientific paradigm, the self-regulation process cannot succeed without an *extrinsic rational dialectic* whereby students are confronted with scientific evidence, and asked explicitly to assess the *commensurability* between their own ideas and the scientific ones. Classmates should provide empirical and rational evidence, whenever possible, and peer discussion should follow. However, there are times when the instructor needs to provide such evidence, especially when confronting an across-the-board incommensurability or when a new conception (concept, law) needs to be introduced that has no match in student knowledge state.

Figure 5

The modeling cycle presented in Figure 4 is the one that our experience has shown to be the most effective learning cycle. It is intended for comprehensive model construction, but it can be easily adapted for the development of a specific concept or a specific law that will ultimately be used in the composition and structure of a given family of models. A complete cycle requires ten to fifteen class periods, depending on the complexity of the model being constructed and student knowledge state. In the event of some practical constraints, some steps (mainly MLC3, MLC4, MLC5) may be curtailed in some respects provided that it is ensured that students end up constructing the targeted model comprehensively and meaningfully.

The *exploration* stage is meant for students to discover the limitations of prior knowledge, be it scientific or not, and realize the need to construct a new model in order to answer specific questions that cannot be answered with models learned so far. To this end, students are first confronted with real world situations and asked to analyze them qualitatively with the least guidance possible (Initiation step, in Figure 4). Then, the instructor intervene by asking students to describe and/or explain quantitatively certain aspects of the presented situation(s) that fall outside the domain of familiar models. Once students realize the unsuitability of the latter models (Impasse), they can be guided to propose a preliminary qualitative sketch of alternative models that can do the job (Nominal models).

The *invention* stage is intended to reach a consensus on as much details as possible of one candidate model that can answer the questions above, as well as on what need to be done in order to assess the validity of the proposed model and complete its construction. As a first step, students are asked to negotiate among themselves the various alternative models they had proposed earlier until they agree on a unique candidate model with specific hypothetical composition and structure (Scientific model in perspective, in Figure 4). Then they are asked to propose an experimental plan that can serve to evaluate and refine the candidate model, as well as appropriate criteria for assessing the outcomes and establish what may be considered as a corroboration (or refutation) of each component of the model (Experimental design).

In the *formulation* stage that follows, students are instructed to carry out the proposed experiment and analyze its outcomes in order to complete the construction of the targeted scientific model according to the model schema of figure 2. The experiment is first conducted in individual groups of three or four students each. Every group would then analyze respective results separately and prepare a group report that outlines quantitatively the composition and structure of the completed model. Next, groups compare reports in the classroom and agree on all aspects of these two dimensions while resolving any residual differences left from MLC4 (Model refinement, in Figure 4). Finally, the new model is compared to other models in its family and integrated in the respective theory, tentatively at this point since the model potentials have not been tested yet (Preliminary model integration).

In the *exploitation* stage, a model gains its full significance following its use in describing, explaining, predicting, controlling and inventing situations of various levels of complexity. Model exploitation progresses from: (a) routine drilling exercises bearing on a limited number of aspects in the model composition or structure (Elementary exploitation, in Figure 4) to (b) creative endeavors that necessitate a comprehensive use of the model in question, along with other models, in a way that fosters best the paradigmatic evolution advocated in this article (Paradigmatic exploitation). The stage ends with a synthesis of all new lessons learned during the entire cycle in order to consolidate all aspects of the new model and integrate it meaningfully and efficiently in the respective theory.

End of chapter exercises (and problems) commonly found in traditional physics textbooks constitute only a modest proportion of exploitation exercises called for in our modeling cycle. These paper-and-pencil exercises present some empirical data –fictitious at times– which students need to match with specific model components. They thus require a particular dialectic that takes students from the empirical world described in a problem text to the rational world of physics. We call these exercises *application* exercises. In MLC exploitation exercises, we include more authentic tasks than paper-and-pencil problems; tasks that require a variety of empirical and rational dialectics (Figure 6). We do so in order to help students behave like physicists, and realize the utility of a model in all conceivable contexts and from all viable perspectives.

Figure 6

Problem solving is a modeling activity conducted following specific guidelines in MLC in order to sway students away from futile trial and error tactics and bring them in steps with physicists. In this respect, students are encouraged to develop systematic schemes for solving physics problems of the type shown in Figure 7. This scheme serves for the resolution of application problems, and can be easily adapted to other types of problems distinguished in Figure 6. It 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 the suitable composition and structure components (Figure 2), and then represent them 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, 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 with their implications on the models employed, including any possible refinement of these models and the respective theory.

Figure 7

Student evolution under modeling instruction

Modeling theory has been, and continues to be, corroborated in many respects and in different forms (Halloun, 1996a, 1996b, 1998b; Halloun & Hestenes, 1987, 2000; Wells, Hestenes & Swackhamer, 1995). Our research has been constantly showing that modeling instruction is more effective than any other approach in promoting the paradigmatic evolution we argued for in this article. More specifically, it has shown the following effects in high school and introductory college physics courses:

- Students are motivated to learn physics meaningfully instead of by rote, especially through modeling activities pertaining to everyday life and through collaborative inquiry.
- Models and modeling schemata provide students with effective means for organizing their knowledge coherently and using it efficiently.
- Modeling activities allow students to develop scientific aptitudes and attitudes they commonly miss under conventional instruction.
- Reflective inquiry allows student to resolve incommensurabilities that traditionally

remain indelible between their common sense knowledge and scientific theory.

- By the end of modeling instruction, the gap is narrowed significantly between students who start their physics course with average and low competence and those who start it with high competence.
- Modeling skills developed in a physics course are transferred to other courses.

Many educators have argued that the state of physics education cannot be improved unless physicists bring into their classrooms whatever modeling practices they resort to in their scientific research (Clement, 1989; Nersessian, 1995; Pollak, 1994). This position is clearly supported by what our own approach is bringing about in physics courses of different levels. Our success has been primarily due to: (a) empowering students with effective modeling tools, the most important of which are modeling schemata, and (b) engaging them into structured learning cycles whereby they play systematically "the game [of] professional scientists called 'creating and shooting down models'" (Pollak, 1994). The deviation thus taken from conventional instruction is not easy and, most likely, not comfortable for some; but it sure is worth the effort!

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Free particle

This model refers to physical objects at rest, or in linear translation with constant velocity, being subject to no net force ($\Sigma \mathbf{F}_i = 0$).

Uniformly accelerated particle

This model refers to physical objects moving with constant acceleration in a linear or parabolic path under a net constant force ($\Sigma \mathbf{F}_i$ = constant).

Bound particle in harmonic oscillation

This model (often called simple harmonic oscillator) refers to physical objects undergoing simple harmonic motion under a net force that is proportional to their displacement from a center of force ($\Sigma \mathbf{F}_i \propto \Delta \mathbf{r}$).

Bound particle in uniform circular motion

This model refers to physical objects undergoing a uniform circular motion under a net centripetal force ($\Sigma \mathbf{F}_i \propto \mathbf{r}/r^n$) of constant magnitude.

Particle under impulsive interaction

This model refers to physical objects whose linear momentum changes significantly while subject, for a very short period, to a variable net force ($\Sigma \mathbf{F}_i = \mathbf{f}(t)$), like in the case of collision.

Figure 1: *Basic particle models of Newtonian Theory*

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. The content of each *basic* particle model consists of a single, dimensionless object: a particle.

Domain: Physical systems and phenomena that the model can describe and/or explain, in some respects, and to a certain degree.

Composition: Conceptual entities that represent two sets of physical objects: (a) the set of objects inside the represented systems (content), and (b) the set of agents outside (environment) that interact with the objects inside, as well as respective object and interaction properties (descriptors).

Structure: Relationships among the descriptors of various objects and agents, often expressed in the form of state, interaction or causal laws. Depending on the type of structure included in the model, a model can be descriptive and/or explanatory. Kinematical models of Newtonian mechanics are descriptive, dynamical models are explanatory.

Organization: Relationship to other models in a given scientific theory.

Every theory provides appropriate *classification schemes* for grouping various models into *families* of models, the most fundamental of which are the families of basic models. A *basic model is* one with simple composition (often consisting of one object) and simple structure (often limited to describing and/or explaining one elementary phenomenon).

Figure 2: *Model schema* (Halloun, 1996a)

Domain: Physical systems or phenomena displaying a common pattern that can be somehow represented by the concept. 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.

Expression: Types of depictions (symbolic, iconic, mathematical) that can be used to express the concept and operate with it, as well as associated semantic rules.

Organization: Criteria and schemes for classifying the concept, as well as conceptual means, and related syntactic rules, for relating it to other concepts within the context of specific models.

Quantification: Means for measuring the concept, especially when a descriptor, and laws and rules that govern such measurement in an appropriate unit system.

Employment: Rules and means for using the concept in the real and conceptual worlds, especially within the context of specific models.

Figure 3: *Concept schema* (Halloun, 1998a)

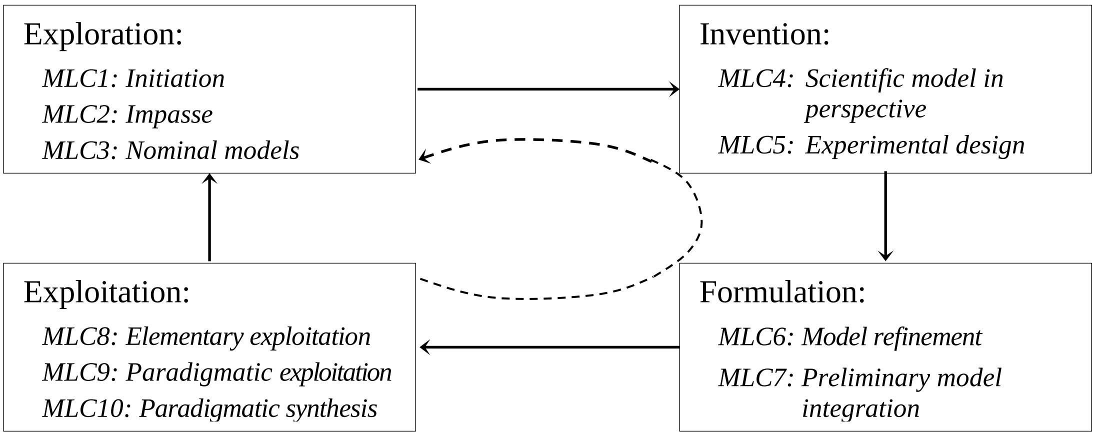

Figure 4: *Modeling learning cycle* (Halloun, 2000)

The dotted, curved arrow indicates that one may go back at any time to a previous cycle.

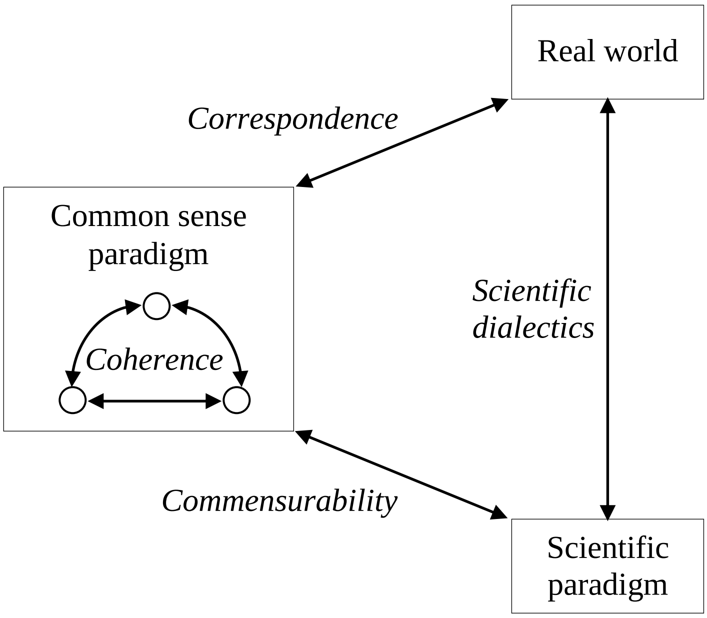

Figure 5: *Rational-empirical dialectics for the evolution from the realm of common sense to the realm of science*

Problem Type	Required dialectic	Objectives
Application	Empirical $\rightarrow$ 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 $\rightarrow$ 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 $\rightarrow$ 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 1).
Extrapolation	Rational $\rightarrow$ 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.

Figure 6 : *Modeling problems taxonomy* (Halloun, 2000)

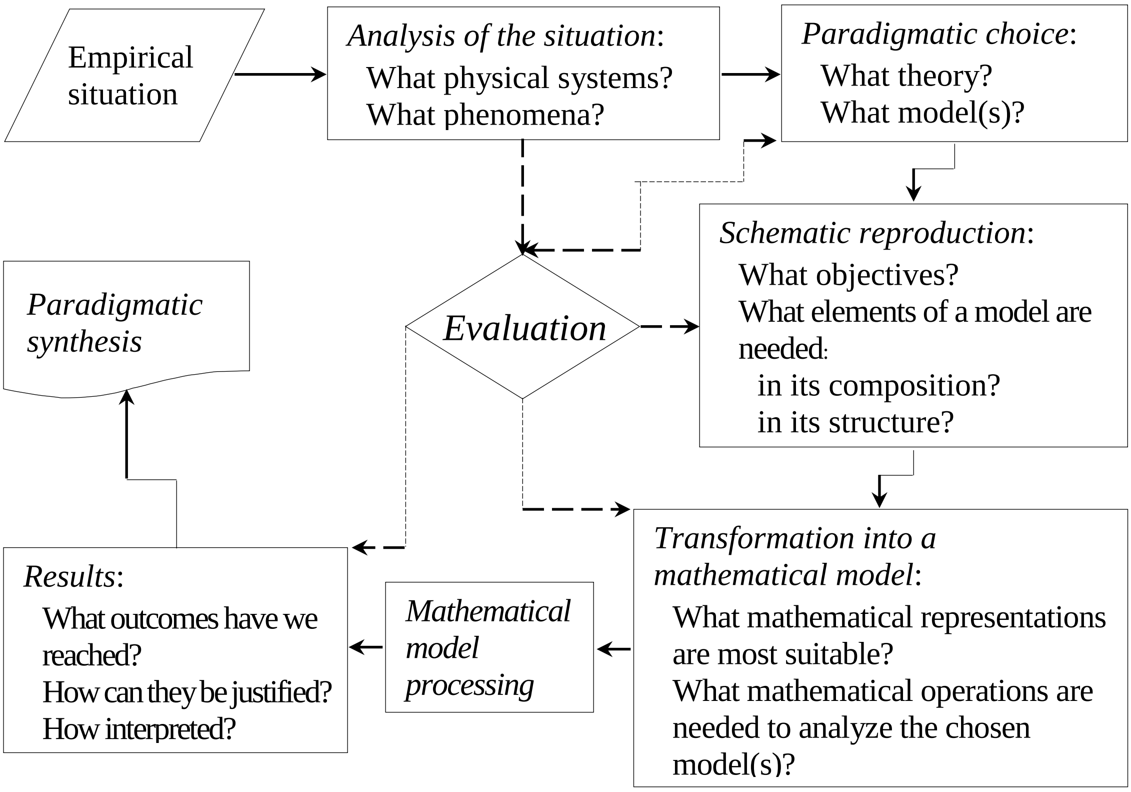

Figure 7: *A modeling approach for solving application problems*