MODEL-CENTERED, ASSESSMENT-GUIDED LEARNING AND INSTRUCTION IN SCIENCE

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ABSTRACT

Conviction prevails in the educational community that meaningful and equitable learning of science is achieved when: (a) course materials are aligned with scientific theory and inquiry, and (b) instructors systematically rely on assessment to insightfully mediate student learning. Our research shows that this can best be achieved when modeling schemata are systematically used: (a) to structure course content around a few basic models, and promote model construction and deployment in the classroom, and (b) to systematically assess and regulate student knowledge throughout well-structured modeling cycles. Modeling schemata explicitly lay out the structure of scientific models (and other conceptual components) that students need to develop in any science course, and spell out cognitive processes in which students need to engage for successful model construction and deployment. Such schemata thus provide instructors with reliable tools for setting the taxonomy of course materials, and for subsequently designing instruction and carrying out authentic assessment that readily feeds into learning and instruction in meaningful and constructive ways. This paper outlines the foundations of model-centered, assessment-guided pedagogy. Practical aspects of such pedagogy, and especially the utility of modeling schemata at all levels of assessment-guided learning and instruction, will be discussed during my talk at the conference.

CONTENTS:

Educational research in the last three decades has systematically shown that students of all levels often complete and pass their science courses without necessarily understanding what their courses are all about (Bransford, Brown & Cocking, 1999; Halloun, 1986, 2001b; Halloun & Hestenes, 1985, 1998; Helm & Novak, 1983; Novak, 1994; NSB, 2004, 2006). Researchers and concerned educators worldwide have argued and shown that at least two major reasons stand behind this failure. One reason is inherent to the structure and delivery of traditional course materials, the other pertains to assessment (Bransford et al., 1999; Hake, 2002; NRC, 2001).

Course materials are traditionally presented in textbooks and taught in the classroom in ways that fail to empower students to evolve into the realm of science. Upon the completion of a given science course, students fail to realize the nature and structure of the scientific episteme targeted in the course, and to develop anticipated skills of scientific inquiry. An episteme consists of the body of conceptual knowledge accepted by a given professional community (e.g., the community of physicists, biologists or other scientists). A scientific episteme consists primarily of a coherent set of corroborated scientific theories. Skills of scientific inquiry extend from those required for the construction of target aspects of a given scientific episteme to skills needed for the deployment of such aspects in the real world.

Calls have long resounded in the educational community for authentic assessment that promotes meaningful and equitable learning. Nevertheless, various forms of traditional course and large-scale assessment (including state or other exit exams, where mandated) are, to a large extent, still promoting rote learning and serving primarily to rank-order students and sift out the minority of “talented” self-learners.

This paper discusses how teachers and other stakeholders can overcome such shortcomings of science courses by aligning course materials and learning activities with scientific episteme and inquiry, while continuously guided by the outcomes of assessment. The paper comes in four sections. The first section discusses the relationship between assessment and instructional design and practice. The second section outlines how pedagogy can successfully recapitulate science by letting models and modeling play a central role in any science course. The third section presents modeling schemata as fundamental tools for designing assessment-guided instruction. The fourth section argues that teachers need to carry out normative, authentic assessment using modeling schemata for meaningful and equitable learning.

The paper lays the theoretical foundations of the author’s talk at the conference. Such foundations will be briefly overviewed during the talk which will be devoted to discuss the practical aspects of the pedagogy presented herewith, and especially the utility of modeling schemata in assessment-guided lesson planning and implementation.

1. Assessment-guided learning and instruction

Learning and instruction are still overwhelmingly test-driven virtually all around the world, despite all reform movements that have lately been calling to the contrary (AAAS, 1990; AAC&U, 2002; Bransford et al., 1999; NRC, 1996, 2001, 2002). Students, parents and administrators ascertain the value of instruction in terms of student scores on course exams, and especially on large-scale state or exit exams where such exams are instituted. They all do so without necessarily heeding for whether or not these scores are reliable indicators of student understanding of tested materials. Teachers are thus driven to teach to the test, and to allow students learn even by rote just enough material to score well on various exams, so that their administrators remain satisfied with their accomplishments. Assessment is thereby conceived as an end by itself rather than means to a more dignifying end: meaningful and equitable learning of any discipline.

To turn things around, learning and instruction need to be *assessment-guided rather than test-driven*. Classroom assessment should be considered not for merely deciding the fate of students in a given course, but especially for diagnosing student difficulties at various points of instruction so that appropriate learning activities may be designed and carried out to help students actively engage in self-regulation, and meaningfully evolve toward the anticipated level of understanding and performance. Large-scale assessment should be meant to provide reliable evidence about student meaningful learning of a given discipline rather than an indication of student capacity for rote learning or ability to memorize and spontaneously reproduce specific content or problem solving routines.

Traditional classroom and large-scale assessments thus often fail to provide reliable evidence about student learning, evidence that teachers and other concerned educators can use to make informed and viable decisions about instruction, pedagogy and curriculum development. Research in the last three decades has consistently shown that major shortcomings of common formative assessment are about: (a) ascertaining the extent to which students meaningfully learn course materials, (b) identifying progress or evolution paths of individual students throughout the course of instruction, and (c) tracking student evolution along these paths in meaningful ways.

Such shortcomings are primarily due to the fact that the results of traditional assessment are presented in the form of numerical or letter scores that do not necessarily reflect what a given student has actually learned or missed from the tested topics. The problem extends to all numerical measures of traditional assessment whether norm-referenced or criterion-referenced. Traditional norm-referenced assessment results in grades or scores that allow ranking students relative to one another or to some norm group of students (high or low achievers). Criterion-referenced assessment often positions students relative to preset score intervals that do not necessarily reflect a cognitive or epistemological hierarchy of what students were tested about. In both types of assessment, two students may receive the same score (or letter grade) without necessarily achieving, or failing to achieve, the same expected outcomes, and a student may receive a higher score than another without necessarily achieving outcomes of higher cognitive order. The philosophy of all forms of traditional assessment needs to be significantly and feasibly modified so as to curtail the shortcomings mentioned above, and end with long-awaited authentic assessment. As we discuss in sections 3 and 4 below, our research shows that test content can be carefully chosen, and student achievement may be systematically graded and normalized so as not to merely rank students relative to one another or to a preset scale, but to *mark individual students' position on a cognitive evolution path that maps on the epistemology of the discipline* being studied. A student score (or any other measure) would then tell where exactly a student stands on this path, and more importantly, it would reliably tell what a student has actually learned and missed in her/his course or program of study.

Assessment subsequently becomes *authentic* in the sense that it would provide valid, reliable and transparent indicators of what students have actually learned and what they can do with their knowledge, and not just a rough estimation of their capacity to memorize and recall things by rote. Authentic assessment brings about outcomes: (a) that students can readily use to evaluate and regulate their own conceptual knowledge and skills, and (b) upon which teachers can reliably rely to ascertain students' achievement and diagnose their difficulties, so that they may determine how to mediate learning successfully. More specifically, authentic assessment enables teachers (and all concerned stakeholders, especially curriculum developers): (a) discern knowledge that is critical for success and meaningful learning of course materials, (b) ascertain how successfully students develop such knowledge at specific points of instruction and how they evolve in the course of instruction, and

(c) interpret the outcomes of assessment so that informed and constructive decisions can be made about learning and instruction (as well as about various curricular components).

2. Middle-out, model-centered scientific episteme

Traditional instruction fails its mission partly because it is test-driven, but mostly because, in the first place, it does not empower students for meaningful and equitable learning of course materials. The case is especially true in science where students are driven to learn by rote loose bundles of theoretical statements and problem solving routines. Research has constantly shown that students often complete and pass their science courses without necessarily understanding what science is all about (Bransford et al., 1999; Cobern, 1995; Hake, 2002; Halloun, 1986, 2001b; Halloun & Hestenes, 1985, 1998; Novak, 1994; NRC, 2001; NSB, 2006). Prominent reform programs are calling for science curricula to reverse the situation by aligning course materials with scientific episteme and practice in ways to help students meaningfully understand the structure of scientific knowledge and develop skills of scientific inquiry (AAAS, 1993; NRC, 1996, 2002; NSTA, 1995).

A scientific *episteme* is a body of conceptual knowledge accepted by a community of scientists. It consists primarily of a set of scientific theories that have been corroborated in the real world, i.e., theories whose viability (validity and reliability) has been established through sufficient evidence in the real world. A scientific theory is, for us, a conceptual system that consists of: (a) a set of models or families of models, and (b) a set of generic rules and theoretical statements (axioms, laws, etc.) that are particular to the theory in question and that govern model construction and deployment. The theory is corroborated indirectly when its models fulfill, to certain extents, specific functions in the real world. A scientific model *represents*, in some respects and to a certain extent, a particular *pattern* in the structure and/or behavior of real-world systems, and serves specific *functions* regarding the pattern in question. These functions may be *exploratory*, i.e., about pattern description, explanation, post-diction or prediction, or *innovative*, i.e., about pattern reification through control or change of existing physical realities (systems or phenomena), and/or invention of new realities like in technology (Halloun, 2000, 2001, 2004a, 2007a).

Prominent educational reform programs agree that the construction and deployment of *scientific conceptual models* are *critical* for reaching high levels of scientific literacy or proficiency, and that science courses need to help students understand the pivotal role of models in scientific episteme and of modeling in scientific inquiry (AAAS, 1993; NAGB, 2004; NRC, 1996; OECD, 2003). Our work on modeling theory and assessment highly resonates with this position (Halloun, 2000, 2001, 2004a & b, 2007a & b). Our work also resonates with cognitive research that shows the importance of models and modeling in all sorts of human endeavor (Bower & Morrow, 1990; Gentner & Stevens, 1983; Giere, 1988; Johnson-Laird, 1983; Johsua & Dupin, 1989; Lakoff, 1987), and that implies that models occupy the basic level in *middle-out* organization of human knowledge (Lakoff, 1987).

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” (Fig. 1). Categories in the middle are *basic* in the sense that: (a) they ensure the best way possible 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.

Rosch and other cognitive psychologists concentrated their work on *prototypical* or *familiarity criteria* in their “general-to-specific hierarchy”. We believe, and our work has begun to show, that the middle-out hierarchy is generic, and that it extends to all sorts of classification criteria. For instance, this hierarchy still holds when *intrinsic structural criteria* are adopted with respect to either the physical world (as seen from a human perspective) or the conceptual world as indicated in Figure 1. In this perspective, models occupy the middle of conceptual hierarchy, between theory and concept in any scientific episteme, just like solar systems occupy the middle of physical hierarchy between a galaxy and its planets.

The model-centered, middle-out structure of scientific theory ensures theory coherence and consistency from an epistemological perspective, and it facilitates people’s 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. 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, the word model is seldom used in reference to other scientific models, which would give students the false impression that Bohr’s model may be about the only

Categories Hierarchy (according to Eleanor Rosch & George Lakoff)

SUPERORDINATE	Animal	Furniture
BASIC LEVEL	Dog	Chair
SUBORDINATE	Retriever	Rocker

Furniture ← Chair → Rocker

Our extrapolation to science:

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 1. Middle-out hierarchies.

The term “hierarchy” takes here a new meaning; it is no longer restricted to a linear, top-down or bottom-up, order.

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 to develop a coherent, model-based, picture of scientific theory and episteme, and they 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 have learned at school that matter consists of elementary particles and should no mention about the atom was ever made.

Models in a given scientific theory are, for us, also categorized in a middle-out hierarchy as shown at the bottom of Figure 1. In the middle of model hierarchy are basic models. A *basic model* is one that is simple enough to facilitate student learning of fundamental tenets and conceptions (concepts, laws, etc.) of the respective theory and of fundamental tools and skills of scientific inquiry. A basic model is yet 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 2 for illustration. A student needs to understand the entire set of basic models so that s/he could meaningfully learn the theory in question, and realize a meaningful paradigmatic evolution.

At the subordinate level of model categories are subsidiary models. A *subsidiary model* is a simplified basic model, a particular case which students may usually be most familiar with, 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 for the progressive construction of the uniformly accelerated particle model (Fig. 2). At the superordinate level of model categories are emergent models. An *emergent model* is one that

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 2. 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.

may be constructed by putting a given basic model together with one or more other models in order to represent a pattern that cannot be represented by either 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 shown in Figure 2, the uniformly accelerated particle model and the bound particle in uniform circular motion.

A science course, especially at the secondary school and college (introductory university) levels, is usually about a particular scientific theory, and sometimes about a set of interconnected theories. The course content can be organized around a number of models that may be graded into categories of increasing structural and functional, and thus *epistemic*, complexity. Each category characterizes a cognitive evolution level that students need to attain at a certain point of instruction. Our research suggests that models of a given theory, and thus course content, can be pedagogically classified into three categories of increasing epistemic complexity (Fig. 3). The first category includes *primary models*. These are *simple basic models* relative to which students usually have the richest repertoire of subsidiary models, and thus in the context of which students can begin to develop the most fundamental conceptions of the theory (generic concepts, laws and other theoretical statements). The second category includes the rest of, and more complex, *basic models*. The third category includes *emergent models*. For example, the five particle models of Newtonian mechanics outlined in Figure 2 are basic models typically targeted in secondary school and introductory university physics courses. The first two models in this figure, the free particle model and the uniformly accelerated particle model, make up the category of primary models Emergent models in classical mechanics courses usually include the model of a particle in uniformly accelerated circular motion, models of particles in elliptical motion and other types of motion with variable acceleration.

The three categories are organized and graded in such a way that students cannot meaningfully learn any model in a given category before learning all models in the lower category. The three categories are thus separated by *critical* demarcation lines. They are critical in the sense that at the level of each line is set a *threshold* of understanding that students need to meet before crossing into the upper category. Two *critical thresholds* can thus be set in any given course: the *basic threshold* between primary models and the rest of

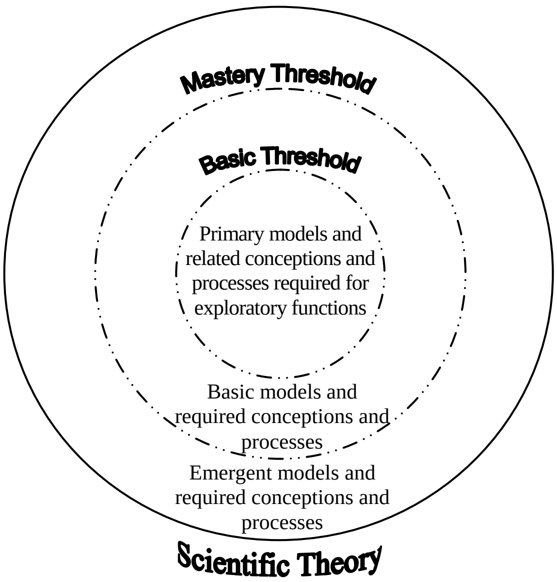

Figure 3. Model-based content categorization and cognitive evolution in a science course.
Evolution from one stage to another is not possible unless students meaningfully attain a particular critical threshold.

basic models, and the *mastery threshold* between basic and emergent models. As we discuss in section 4 below, *formative assessment* in any given course needs to be carried out in specific ways within each category, and *summative assessmen*t needs to concentrate on the critical thresholds so as to determine the opportune moment for moving in the course of instruction from one category to another (Fig. 3). Both forms of assessment can be efficiently carried out using modeling schemata discussed in the following section.

3. Modeling schemata for instructional design and assessment

For efficient learning, teachers need to put together and forth coherent and systematic lesson plans that are flexible enough to accommodate both scientific rigor and pedagogical concerns. They especially need to integrate assessment with instruction so as to determine the most effective ways for mediating meaningful and equitable learning of course materials. To these ends, teachers need to be empowered with appropriate tools to lay out course content and design learning activities and assessments that cover comprehensively all fundamental aspects of course materials. The most important of these tools are content and process schemata.

A *schema* is, for us, a generic organizational template for spelling out: (a) all salient features that a student needs to know about a given conception (content schema), or (b) all processes that the student needs to master for meaningful construction and deployment of the conception (process schema). In our modeling theory, we consider that patterns extend from the physical world to the conceptual world, and that there is a pattern in the structure (and related processes) of all scientific conceptions of a given type, be it concepts, laws or any other type of theoretical statements (axioms, definitions, etc.), or models. We further consider that two conceptual patterns are most critical to realize the middle-out, model-centered perspective of scientific theory and episteme (Fig. 1). These are the pattern underlying the structure (or related processes) of all scientific concepts, and the pattern underlying the structure (or related processes) of all scientific models. With these two patterns we associate respectively the concept schema and the model schema. The two schemata are generic in the sense that, for content or processes, there is only one concept schema to cover all aspects of any scientific concept, and only one model schema to cover all aspects of any conceptual model in any given scientific theory. Furthermore, the two schemata are *modeling schemata* in the sense that they promote construction and deployment of concepts and models from the perspective of modeling theory in science education (Halloun, 2001, 2004a).

3.a Content schemata

The two modeling schemata are discussed elsewhere with ample details from a content perspective (Halloun, 2000, 2001, 2004a). We briefly review them in this subsection, and we provide practical examples on their utility in the context of perhaps the most familiar scientific theory of them all, the Newtonian theory of classical mechanics.

The *model schema* is a four-dimensional template for putting together any scientific model, at least those models that are the object of study in secondary school and college science. 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 displaying the modeled pattern.

The *domain* of a scientific model specifies what physical realities (systems and/or phenomena) the model represents in the real world, and under what conditions. The realities in question, called model *referents*, display the physical pattern that the model represents.

Uniformly Accelerated Particle Model

1. **Domain**

*What **pattern** does the model **represent** in the real world?*

All physical systems that are in *translation* with *constant acceleration* in inertial reference systems. A given system interacts with one or many physical agents that exert on it a net *constant force*.

2. **Composition**

*What **concepts** does the model consist of?*

Objects: *One* particle representing a system in consideration, and depicted by a geometric point in a coordinate system representing the reference frame where the motion takes place.

Environment: Two types of agents are distinguished in Newtonian mechanics, those of interaction at-a-distance (or long-range interaction), and those of contact interaction.

Object descriptors refer to *intrinsic* and *state properties* of the particle-like system. Only one intrinsic property is accounted for in any particle model: the mass of an object. State properties are the kinematical properties of the object. They include position, displacement, velocity, acceleration, kinetic energy, etc. In a coordinate system, state properties are depicted in a *motion map* consisting of a trajectory on which can be shown position, velocity and acceleration vectors at instants of interest.

Interaction descriptors include, among others, the concept of force. Forces exerted on the particle-like system by its agents are often depicted by arrows in a *force diagram*. The net force is evaluated using the superposition principle (Newton's 4th law or law of composition).

3. **Structure**

*How are concepts **related** to each other, and what is the subsequent **function** of the model?*

Topology facet: The geometric structure, if any in this model, is often restricted to the relative position of the particle-like object and long-range agents.

State facet: The translation of the particle is described with *state laws* (often called equations of motion) involving only kinematical concepts, such as:

$\mathbf{a}$ = constant $\qquad \Delta\mathbf{v} = \mathbf{a}t \qquad \Delta\mathbf{r} = \mathbf{v}_o t + \frac{1}{2}\mathbf{a}t^2 \qquad \Delta\mathbf{v}^2 = 2\mathbf{a}\Delta\mathbf{r}$

These laws can be depicted with appropriate *graphs*, *relational diagrams* and/or *motion maps*.

Interaction facet: Object-agent interaction is expressed with appropriate interaction laws, like the Newtonian law of universal gravitation, or the Coulomb law of electrostatic interaction.

Causal facet: Change of state, e.g., change in the particle's velocity, is explained by *causal laws* such as Newton's 2nd law (dynamical law) or the Work-Energy theorem (conservation law).

The model may be kinematical (descriptive function), and/or dynamical (explanatory function).

4. **Organization**

*How is the model **integrated** in its theory?*

Newtonian Theory relates the uniformly accelerated particle model to:

- other models within the family of particle models (Fig. 2).
- rigid body models and other families of models (e.g. fluid models) within the theory.

Rules are established within the theory to combine this model with other basic models in order to study physical systems undergoing more complex motions. For example, this model can be combined with the model of bound particle in uniform circular motion in Figure 2 to come up with the *emergent model* of a particle in circular, uniformly accelerated translation.

Figure 4. The content model schema applied for specifying what needs to be learned and assessed about the uniformly accelerated particle model in Newtonian theory at the secondary school level.

Model *composition* consists of concepts representing *primary* constituents and respective properties of physical systems, i.e., only those constituents and properties that are salient to the pattern. Concepts of interest to us at this level are mainly of two types: object-concepts and property-concepts. *Object-concepts* (or conceptual objects) represent physical bodies that significantly contribute to the making 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. *Property-concepts* (or *descriptors*) represent primary physical properties of objects and agents, and of their mutual interaction.

Model composition is meant to discern between primary and secondary aspects of a pattern, i.e. between those aspects that need to be accounted for in the modeling process and those that may be ignored within the considered limits of precision and approximation. In model composition, primary object and property concepts are only listed and not related to one another. Model structure spells out relevant relationships among primary features of the pattern represented by the model, and set the function of the model.

Model *structure* can be defined along four sub-dimensions, or facets, each dealing with a specific aspect of model referents in relation to pattern formation. These are: (a) the topology facet that lays out the *geometric* structure of various objects represented in the model, (b) the state facet that *describes how* each object behaves, (c) the interaction facet that specifies how various objects *interact* with each other, and (d) the cause-effect or causal facet that *explains why* objects behave the way they do. 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.

Model *organization* situates a given model in the respective scientific theory. It establishes how the model in question differ from, or is similar to, other models in the theory, and how it may be extrapolated in the construction of more complex models.

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 (Fig. 4). 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 (Halloun, 2000, 2001a, 2004a). They are concisely presented below for property-concepts or descriptors, and illustrated in Figure 5 with the concept of force in Newtonian theory.

The *scope* of a concept sets the domain and function of the concept. 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) that depends on the nature of the property.

The *expression* of a scientific concept is done objectively so as to name it and feature it in ways to clearly distinguish it from any other concept. Particular *semantics* establish what the concept expression actually delineates in the real world or the rational world of scientific episteme. 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

The concept of force in Newtonian theory

1. **Scope**

   *What does the concept **represent** in the real world, and what is its **function**?*

   The concept of force represents agent-object *interaction*. A force of particular characteristics is associated with a particular kind of interaction.

   No physical body can act on itself. An interaction takes place between at least two bodies, an « agent » (acting body) and an « object » (body acted upon) whose state is being investigated.

   The concept of force is *explanatory*. It explains the *change of state* of a given object, more specifically the change of its linear momentum (or velocity).

   No change of state takes place in the absence of any (net) interaction. A change of state reflects the presence of unbalanced interactions, and may be *explained* with the force descriptor.

2. **Expression**

   *What is the concept **called,** and how is it **featured** in scientific discourse and episteme?*

   Force is the name of the concept, and no other name can be used to call this concept. As a vectorial concept, it is often represented by an arrow in appropriate force (vector) diagrams, and denoted symbolically by a bold letter in algebraic representations (mathematical equations).

3. **Organization**

   *What is the concept **type**, and how is it **related** to other concepts in a given scientific theory?*

   The concept of force is a *prime interaction* descriptor. It does not derive from any other concept, though other concepts may derive from it (e.g., the derived concept of work). It is implicitly defined through Newton's four laws of dynamics.

   The concept of force is related to: (a) the *intrinsic* properties of respective object and agent through *interaction laws* such as Newton's law of universal gravitation, (b) its *effect* on the object to which it is applied through *causal laws* (e.g., Newton's second law of dynamics, often expressed in the form $\mathbf{F} = m\mathbf{a}$), laws that relate the interaction concept of force to object descriptors.

4. **Quantification**

   *How is the concept **measured**?*

   Force is a *vectorial* concept (as opposed to *scalar*, like the concepts of mass or temperature), and hence its measurement requires the specification of a direction, a magnitude and a unit which is the Newton (N) in SI.

   Force is an *extensive, additive* and *ratio-type* concept (as opposed respectively to *intensive, non-additive* and *interval-type concept*, like temperature).

   A force is *indirectly* measured physically; there are no direct means (or physical probes) for comparing a given force to a standard force in the same way, say, the length of an object is physically measured by comparing it to the graduation of a ruler. A force is always measured through its effect on a given object, like stretching or compressing a spring.

   The effect of a force on an object is instantaneous and lasts as long as the force is exerted on this particular object. It stops only when the force is no longer exerted on the object.

   No two forces can be added together (through Newton's fourth law or law of composition) unless they are exerted simultaneously on the same object.

   The dimension of a force may be given symbolically by: $[Force] = \dfrac{[Mass][Length]}{[Time]^2}$

   The characteristics of a force are invariant under Galilean transformations, i.e., when changing inertial reference systems.

Figure 5. The content concept schema deployed in spelling out some salient aspects that secondary school students need to know about the concept force in Newtonian theory.

close as possible to a comprehensive expression of the concept, since no single form can actually do so alone.

Concept *organization* sets criteria and guidelines for classifying a concept and for relating it to other concepts, all along with appropriate syntax rules. Three concept categories may be distinguished in science: object-concepts, property-concepts or descriptors, and logico-mathematical operators (e.g., equality, addition, derivatives and integrals). Syntax rules set how a given object-concept or, especially, property-concept can be related to other concepts of its category, mostly using logico-mathematical operators (e.g., state, interaction and causal laws in the structure of a model).

Quantification specifies how a scientific descriptor can be measured. A major distinctive feature of scientific descriptors is that they are measurable according to well-defined laws and rules (otherwise, a descriptor cannot be scientific). The sort of measurement which the descriptor can be subject to can be set accordingly (nominal, ordinal, interval or ratio), along with the means and procedures which one can resort to for determining values of the concept on a certain scale, and by comparison to a certain standard.

3.b Process schemata

The two content schemata discussed above allow teachers to decide what is needed to put together a given concept or model, but not how students should go about constructing or deploying the concept or the model in question. Process schemata are needed to the latter ends. Model construction and deployment require contextual and generic processes. Generic processes extend to all sorts of models in any scientific theory. For those processes, we define a generic *process model schema* in the form presented in Figure 6. Contextual processes pertain to individual concepts and laws in any given model. Typical processes of the sort are presented in Figure 7 which follows the process concept schema.

The *process concept schema* includes processes that are more context dependent than the generic processes listed in Figure 6. As shown in Figure 7, this schema especially includes processes of semantics and syntax. *Semantic* processes are processes required to determine what a concept represents and under what conditions. They rely on one's understanding of the concept scope. *Syntactic* processes are the ones needed to relate one concept to another. They rely on one's understanding of the concept organization. The process concept schema may also incorporate some of the generic processes listed in Figure 6 that have particular importance in concept construction and, especially, in concept deployment. These include inferential, evaluative and mathematical processes. *Inferential* processes are about various sorts of conjectures that one needs to make while using the concept for exploration or innovation purposes. *Evaluative* processes pertain to all sorts of judgment one needs to make about the viability of the concept. *Mathematical* processes pertain to symbolic representations and operations that one can undertake with the concept.

Students need to develop all processes, including generic ones, in the context of specific physical realities that models and concepts represent. One can never expect students to develop any of these processes in the abstract world. Our position in this respect is consistent with the view of many reformists that "processes have to be used in relation to some subject matter; there is no meaning to a content-free process" (OECD, 2003), at least not at the secondary school and college levels.

There are, of course, many other processes required for meaningful understanding of any course materials. Perhaps the most important of which are dialectic and other cognitive processes extending from intrinsic mnemonics for storing information and retrieving it from memory to extrinsic discourse styles for communicating and negotiating one's own ideas with others. *Dialectic* processes are concerned with the negotiations that one undertakes while constructing or deploying a given conception within one's own rational world and between this world and external worlds (whether the empirical world of natural realities or the rational world of an established science). Such processes and related meta-cognitive control factors are beyond the scope of our discussion in this paper.

Constructing and deploying scientific models

- *Exploratory analysis*. This process is a complex analysis process required to analyze physical situations that one needs to explore (describe, explain, predict or post-dict). It extends from the delineation and setting the boundaries of individual systems in the situation (system / pattern recognition) to the discrimination between primary and secondary constituents and properties of the system (discriminatory analysis).
- *Model adduction*. This process allows one to decide when is it appropriate to use a particular scientific model to explore a given situation, or come up with certain innovations about the physical pattern that the model represents. Model adduction relies heavily on one's understanding of the domain of the model, its function and its organization.
- *Mathematical modeling*. This process is about transforming a conceptual scientific model (or a physical situation represented by the model) into a mathematical model that can be efficiently manipulated in model analysis. Mathematical modeling relies heavily on semantic rules discussed in the process concept schema below, and on one's understanding of the rules of mathematical depictions.
- *Model analysis*. This process is about "running" a scientific model (or, often its mathematical counterpart) to explore a given physical situation. Model analysis relies heavily on syntactic processes discussed in the process schema below, and on one's understanding of the structure of the model and of various mathematical operators used in the process.
- *Model reification*. This is about using a scientific model to control or modify an existing reality, or to invent a new one that manifests the pattern represented by the model. This process relies on engineering and technology.
- *Model evaluation*. This process takes place throughout model construction or deployment, i.e., in conjunction with the other processes listed above. Every step taken through any of those processes need to be evaluated in order to ensure not only the viability of the step in question, but also the viability of the processed model for the situation in which it is used, and to subsequently consolidate the model or refine it in the context of the scientific theory to which it belongs.

Generic inquiry processes.
In addition to the above model-specific processes, there are other generic processes needed in concept or model construction and deployment, or any other form of scientific inquiry. These include: semantics and syntax, critical thinking (including discriminatory analysis and evaluation), analogical and metaphoric reasoning, conjecturing (making assumptions about a particular situation), inference making, analysis and synthesis (in the broad sense), extrapolation, and mathematical processing and interpretation.

Figure 6. The process model schema.

Constructing and deploying the concept of force in Newtonian theory

1. *Semantic processes.*:

- Recognize that the concept of force represents an interaction between at least two real bodies.
- Distinguish between agents and objects. An agent is a distinct body that exerts a force on an object.
- Recognize that particular agents exert forces of particular characteristics.
- Recognize that the concept of force is a vectorial concept and establish the correspondence between a vector (mathematical representation) and the force (physical reality) that it represents.

2. *Syntactic processes.*:

- Realize that an agent and an object exert equal and opposite forces the magnitude of which may be expressed in terms of intrinsic parameters with appropriate interaction laws (e.g., gravitational and electrostatic interaction laws).
- Realize the independence of different forces exerted by different agents on the same object.
- Realize that forces may be added together only when acting on the same object.
- Realize that Newton's Second law ($\mathbf{F} = m\mathbf{a}$) relates a cause (F) to an effect (a), and thus that the equality between the two terms of the given equation represents a causal implication and not an identity.

3. *Inferential processes*:

- Recognize that the state of motion may be defined with the concept of velocity (or momentum) and not with the concept of position in a given reference system.
- Realize that the state of motion changes whenever the direction or magnitude of an object's velocity changes, and that the concept of acceleration may be used to quantify such a change of state.
- Realize that only a change of state as described above needs to be explained, and that the concept of force may be used to explain such a change.
- Alternatively, realize that an object is subject to certain force(s) when its velocity changes.

4. *Evaluative processes*:

- Realize what data need to be collected to determine whether an object is subject to certain forces.
- Be capable of analyzing data and recognizing when outcomes reliably indicate that forces are exerted on an object.
- Recognize the limits of approximation and precision associated with the evaluation of particular forces.
- Be capable of estimating certain forces and establishing upper and lower bounds on such estimations.

5. *Mathematical processes*:

- Representing forces with appropriate vectors (force diagrams), following appropriate semantic rules.
- Operating with force-vectors following appropriate syntactic rules (e.g. breaking a force-vector into components or adding force-vectors in an appropriate coordinate system).
- Coordination of various mathematical representations of a given force.
- Establishing the correspondence between force diagrams and motion diagrams.

Figure 7. The process concept schema deployed in specifying basic processes associated with the concept of force in Newtonian theory of mechanics.

4. Authentic, schema-based assessment

For authentic assessment to serve its purposes, it must satisfy a number of conditions discussed elsewhere with ample details (Halloun, 2007b). Perhaps the most important of all those conditions is that assessment must be *normative*, i.e., conducted in reference to pre-established benchmarks. Those benchmarks are, for us, set by modeling schemata.

Teachers can use modeling schemata throughout the course of instruction, from planning and implementing learning activities to assessing students' understanding of course materials. Those schemata help teachers spell out the *taxonomy* of any conception (concept or model) included in a given course in the manner outlined in the last four figures. Teachers can subsequently ensure that all fundamental aspects of the conception are covered in both instruction and assessment so as to help students meaningfully learn course materials. The taxonomy spelled in line with any of the four figures is especially helpful for *formative assessment*, i.e., for assessment that needs to take place within, and by the end of, any course unit. Outcomes of formative assessment can then help both students and teachers reflect back on, and insightfully regulate, their respective achievements. In this respect, authentic assessment takes learning and instruction in reiterative and not linear paths. A student cannot move on to new materials before having meaningfully learned prior materials. This is particularly the case when it comes to any of the two critical thresholds shown in Figure 3, and especially the basic threshold, that *summative assessment* needs to target.

Figure 8 delineates a taxonomy for all content knowledge that falls just below the critical threshold in a physics course dealing with Newtonian mechanics. Our research and experience has long shown that secondary school and college students fail to understand anything about Newtonian theory unless they master first all elements in the taxonomy shown in this figure. They particularly cannot develop any of the higher content material pertaining to the last three models in Figure 2 unless they first reach the critical threshold delineated in Figure 8. A teacher thus cannot move on in instruction beyond this threshold unless students develop first the content of the latter figure. That is why summative assessment is important, even most critical, at the level of the basic threshold.

Our research has also shown that a taxonomy similar to the one shown in Figure 8 allows teachers and other concerned stakeholders to trace a typical *evolution path* that they can model in instructional design and curriculum development, and against which they can ascertain actual student evolution paths, and subsequently determine the effectiveness of instruction and curriculum. We have devised standardized tests that set the critical and mastery thresholds at special levels of performance, and more specifically at specific scores on such tests. Ample details can be found elsewhere (Halloun, 2004b, and references therein), and will be discussed in my talk at the conference.

1. *Law of Inertia (Newton's 1st law)*

The state of inertia of physical bodies is characterized with a constant velocity (that is not necessarily zero) in Galilean reference systems.

No external cause, and more specifically no interaction, is needed to maintain such a state.

2. *Interaction and Force*

No physical body can act on itself. An interaction takes place between at least two bodies, an « agent » (acting body) and an « object » (body acted upon) whose kinematical and/or dynamical state is being investigated.

The concept of force represents agent-object interaction. A force of particular characteristics is associated with a particular kind of interaction. These characteristics are not affected by the kinematical state of the object (current or past), or by the object interaction with other agents. In particular, motion does not imply force (impetus), and the force exerted by a given agent on an object does not build up or get used up because of the motion of the object.

The force acting on an object lasts as long as the interaction with the respective agent is taking place. It vanishes at the instant the interaction is brought to an end. The same goes for the force effect on the object.

3. *Law of Interaction (Newton's 3rd law)*

Agent and object exert simultaneous forces on one another. The two exchanged forces are equal and opposite, irrespective of the physical or kinematical properties of either body.

4. *Law of Cause and Effect (Newton's 2nd law)*

An object must interact with at least one agent in order to change its state of inertia, and more specifically to change the direction or the magnitude of its velocity.

The concept of acceleration represents the effect of interaction between agent and object. Acceleration and not velocity of object is proportional to the exerted force and inversely proportional to the object mass, and this irrespective of the nature of interaction.

5. *Law of Composition (Newton's 4th law) / Superposition Principle*

Many forces can be composed only if exerted simultaneously on the same object.

Simultaneous interaction of a given object with many agents is identical in cause and effect: (a) to the absence of any interaction when the sum of all forces acting on the object is zero, or, otherwise, (b) to its interaction with a single agent that exerts on it a force equal to the vectorial sum of all forces exerted by the original agents.

The kinematical state of the object may be determined by the superposition of motions that it would have undergone, during the same period, under each dynamical state separately.

6. *State Laws*

The kinematical state of a given object, from a particular moment onward, depends on the velocity of the object at this moment and its interaction with all influential agents. This state is independent of prior motion of either object or agents.

Under the action of a constant force, an object maintains a uniformly accelerated motion following: (a) a linear trajectory when its initial velocity (at the time the force starts acting) is either zero or pointing in the (same or opposite) direction of the force, or (b) a parabolic trajectory when this is not the case with the velocity.

The velocity of a uniformly accelerating object changes in proportion to the duration of motion and not to the distance traveled. For a given acceleration, duration of motion and velocity change are independent of the object mass. When the object slows down until a point where it turns around in the opposite direction, the object does not stop at this point; motion in both directions is symmetric and it takes place all along with the same acceleration.

Whatever their motion in a given reference system, two objects that occupy the same position at a given time do not have necessarily the same speed at this time. However, two objects may have the same acceleration when they move with different velocities.

Figure 8. A partial *content* taxonomy associated with the *basic threshold* in Newtonian theory of mechanics.

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