Scientific Models and Modeling in the Framework of Systemic Cognition and Education

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August 26, 2018

Dear Colleague,

This working paper is part of a number of publications on Systemic Cognition and Education (SCE), its foundations, and its applications in curriculum development and student and teacher education. SCE is a generic pedagogical framework that stems from my work on Modeling Theory in physics and science education and from reliable research findings in neuroscience, cognitive psychology, and education.

I hope that this paper will bring about fruitful discussion about its content and deployment in the development of theoretical essays and practical modules for designing and teaching various science courses at all educational levels.

I would thus greatly appreciate your valuable feedback on both content and prospective cooperation at: halloun@halloun.net.

Please feel free to share the paper with interested colleagues, and to refer to it in any work. You may then gratefully cite it as:

Halloun, I. (2018). *Scientific Models and Modeling in the Framework of Systemic Cognition and Education*. Working paper. Jounieh, LB: H Institute.

Sincerely,

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Abstract

A scientific model is a conceptual system that represents a pattern in the structure and/or behavior of physical systems in the real world, and scientific modeling is a multifaceted dynamic, systemic process that involves model construction and deployment for well-defined purposes, including pattern description and explanation, and system investigation, transformation, and invention. Models and modeling may serve pedagogical purposes, especially in science education and in the framework of Systemic Cognition and Education (SCE). SCE is a generic pedagogical framework grounded in neuroscience, cognitive science, and reliable educational research, and designed to empower learners at all levels with dynamic, systemic profiles for lifelong learning and success in life. To this end, SCE calls to structure the content of any science course around powerful models and modeling habits with a systemic worldview that embraces patterns in human brain and mind. This paper presents an overview of models and modeling in the framework of SCE, and provides modeling tools like the system schema for model construction, a systemic scheme for model deployment, and a rubric for tracking the evolution of student profiles in meaningful ways. Science teachers can readily take advantage of these tools for mediating meaningful and sustainable learning of course materials and development of systemic profiles.

Keywords

Cognition, evolution rubric, model, modeling, schema, system, taxonomy, transaction

Science is primarily concerned with the description and explanation of physical patterns in the universe, from the astronomical scale to the subatomic scale. This helps scientists and other professionals trace the history of physical realities (bodies and phenomena, living organisms included) and predict their future, change and control the state of such realities, discover new realities in the universe, and invent new artifacts of all sorts and scale. Scientists carry out their tasks through modeling inquiry. They construct, corroborate, and deploy conceptual models each of which represents a particular pattern in certain respects and to a certain extent, and serves a particular descriptive and/or explanatory function regarding the pattern in question. Scientific models and modeling can be transposed into pedagogical tools and processes which students of all levels can efficiently take advantage of for meaningful and sustainable learning of scientific theory. This paper discusses how this transposition can be achieved in the context of Systemic Cognition and Education, a generic pedagogical framework for student and teacher education.

The merits of models and modeling processes are being increasingly recognized not only in scientists' work, but, most importantly, in human cognition in general and in science education in particular. In science, models are principal means, if not *the* chief ones, with which scientists: (a) represent, investigate, transform, and impose order on, physical systems and phenomena, and (b) put together scientific theory coherently and corroborate it efficiently (Bunge, 1967; Giere, 1988; Harré, 1970, 1978; Hempel, 1965; Hesse, 1970; Wartofsky, 1968). Some cognitive scientists have even argued that model construction and deployment are not restricted to science, and that related processes and products extend to all sorts of human endeavors (Bower & Morrow, 1990; Gentner & Stevens, 1983; Giere, 1992; Johnson-Laird, 1983; Lakoff, 1987).

Prominent organizations concerned with science education have long been calling for scientific literacy, and for aligning science curricula and pedagogical practices with scientific episteme and practice, as well as with natural human cognitive processes and outcomes (AAAS, 1990, 1993; AAC&U, 2002; NASEM, 2018; NRC, 1996, 2012; NSTA, 1995). To this end, scientific models and modeling inquiry have been constantly considered to be the most effective pedagogical tools and processes. Such calls have been heeded and justified in the works of numerous science educators[1].

This article is the culmination of over three decades of model-based research and instruction into which this author has been engaged in cooperation with many educators based mostly in USA and Lebanon. It presents an overview of what experiment and experience have shown to be efficient teaching practice in bringing about meaningful and sustainable learning of science, especially in secondary school and university courses (Halloun, 1984, 1994, 1996, 1998a & b, 2000, 2001, 2003, 2004/6, 2007, 2011; Halloun & Hestenes, 1987). The article promotes model-based student transaction with physical realities in the context of Systemic Cognition and Education (SCE). SCE is a generic pedagogical framework that calls for educational curricula and settings to be designed as dynamic systems the main function of which is to bring about systemic citizens empowered for lifelong learning and success in various aspects of life (Halloun, 2017a & b, 2019, in preparation).

The article comes in seven sections. It begins with an overview of certain aspects of SCE that bear directly on what the article is about, primarily systemic, model-based transactions with physical realities that help empowering students with systemic profiles. A discussion follows

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[1] See, for example, Bullock, 1979; Casti, 1989; Clement, 1989, 1993; Develaki, 2006; Doerr, 1996; Dominguez, De la Garza & Zavala, 2015; Erduran, 2001; Gee, 1978; Giere, 1994; Gilbert, 1991; Glas, 2002; Hafner & Stewart, 1995; Joshua & Dupin, 1989, 1999; Justi & Gilbert, 2002; Lattery, 2017; Moreira & Greca, 1995; Nersessian, 1995; Nicolaou & Constantinou, 2014; Passmore and Stewart, 2002; Redish, 1994; Shore et al., 1992; Smit & Finegold 1995; Steen, 1990; Treagust, Chittleborough & Thapelo, 2002; Viau, 1994; White, 1993; Windschitl, 2004.

in the second section about how such transactions are carried out in science through conceptual models that represent patterns in the structure and/or behavior of well-delineated physical systems in the real world. In the third section, a four-dimensional system schema is presented for defining any system, scientific models included, along with a taxonomy of learning outcomes that helps systematizing system definition in accordance with the schema. Systemic model construction and model organization in particular cognitive hierarchies are subsequently discussed in the following two sections. Systemic model deployment following a particular modeling scheme and as an integral part of model construction in systemic learning cycles makes the object of the sixth section. This section also includes a rubric that helps teachers trace the evolution of their students' profiles, and design necessary learning tasks, assessments included, to keep profile evolution on track. Following a seventh section that highlights the importance and feasibility of cross-disciplinarity in science courses, the article concludes with a call for science teachers to adopt model-based pedagogy that empowers students for success in life and not for just passing conventional exams.

1. Systemic Cognition and Education

Systemic Cognition and Education (SCE) is a generic pedagogical framework for student and teacher education. SCE is grounded in reliable research in education, and especially in cognitive sciences and neuroscience, and in the history and philosophy of science. According to SCE, our experiential knowledge about the physical world, i.e., knowledge that results from direct experience with physical realities (objects and events), emerges from continuous transaction with this world. The transaction consists primarily of realist-cognitive exchange or negotiations between a given physical reality exposed to our senses and our human mind. The transaction is most efficient, and the emerging knowledge most meaningful and productive, when: (a) all entities involved, including the mind of the person engaged in the experience, are treated as interacting dynamic systems or parts of systems, and when (b) the transaction is part of a comprehensive systemic education that works to empower students for lifelong learning and success in various aspects of life (Halloun, 2017a, 2019, in preparation).

1.1 Human transaction with physical realities

Human transaction with any physical reality involves cognitive processing in the brain of select information our senses relay to the brain about the reality (filtered perception). The process entails negotiations in the brain between filtered perception and prior knowledge, and results in an *emergent conceptual image* of the physical reality stored in our memory. The image represents the reality in question in certain respects and to a certain extent, and is not in any respect a true copy of the physical reality. It is an emergent mental construct that blends in specific ways real afferent data from the reality as relayed to us by our perceptual system along with prior knowledge that is called upon in the memory of each of us to process afferent data and make sense of it.

As indicated in Figure 1, the transaction involves constant evaluation of the conceptual image and invoked prior knowledge, and subsequent regulation of both image and knowledge. Regulation may range from simple image refinement to the construction of an alternative image altogether. It involves changes in prior knowledge stored in short-term and/or long term memory, in order to accommodate image encoding, consolidation, and integration in memory (Halloun, 2017a, 2019).

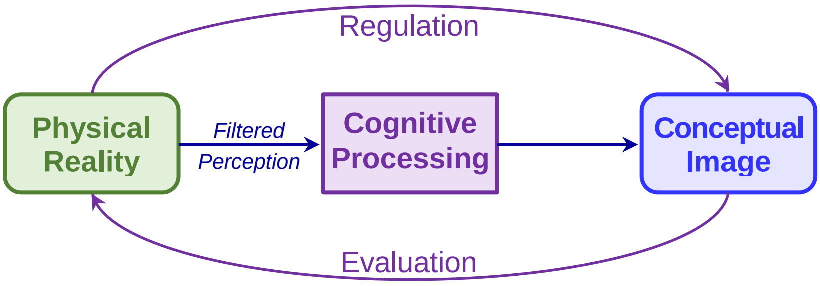

Figure 1. Human transaction with physical realities.

According to SCE, the transaction is most efficient and meaningful if carried out consciously and systematically as a systemic process whereby all involved entities are treated as interacting systems in the manner discussed below. This includes the physical reality, the person(s) involved in the transaction and their brain(s), and the conceptual image that is most meaningful when conceived in the form of a scientific model.

1.2 Systemism

Philosophers and cognitive scientists have long argued for systemism, i.e., for a systemic worldview whereby the entire world around us and within us is considered to consist of interacting dynamic systems. Such a worldview is esteemed optimal for bringing cohesion and coherence to the world around us, as well as to our own thinking, and for making sense of the world and understanding certain aspects therein that may not be easily conceived – and perhaps that may not be conceived at all – without such worldview. In this respect, accomplished people, especially professional experts, have been constantly shown to be distinguished from other people more in how they organize knowledge than in how much knowledge they hold in mind, and more in how they systematically deploy generic skills that cut across various professions, than in how they follow idiosyncratic or profession-exclusive heuristics. System-based organization (model-based, in science) comes then as most effective and efficient for structuring content knowledge. Similarly, systemic thinking, i.e., exploring the world purposely as a world of systems, and consciously constructing, retaining in memory, and deploying conceptual systems, especially scientific models, holds a superior standing when it comes to process knowledge[2].

The importance of a systemic worldview on all aspects of our life has led many reformists to call for "systems-level understanding" of various topics taught at different levels of education (Garcia et al., 2014; Goleman & Senge, 2014; Johanessen, Olaisen & Olsen, 1999; Laszlo, 2015; Liu et al., 2015). Accordingly, some educators have begun integrating successfully "systems thinking" in their teaching (Assaraf & Orion, 2005; Hmelo-Silver, Marathe & Liu, 2007; Mehren et al., 2018; Rodriguez, 2013; Waters Foundation, 2010). We call for a systemic education that explicitly and systematically adopts a generic systemic framework under which all actors (teachers included), organizations (schools and governing authorities included), mechanisms and products (curricula and learning outcomes included) are conceived as systems or parts of interacting systems that work in tandem to serve the major purpose of bringing up systemic citizens.

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[2] See, for example, Assaraf & Orion, 2005; Bachelard, 1934, 1949; Bower & Morrow, 1990; Bunge, 1967, 1973, 1979, 1983a & b, 2000; Čančula, Planinšič & Etkina, 2015; Casti, 1989; Chi, Feltovich & Glaser, 1981; Clement, 1989; Develaki, 2006; Gentner, & Stevens, 1983; Giere, 1988, 1992, 1994; Glas, 2002; Halloun, 2004/6, 2007, 2011, 2017a, 2019; Harré, 1970; Hempel, 1965; Hesse, 1970; Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver, Marathe, & Liu, 2007; Johanessen, Olaisen, & Olsen, 1999; Johnson-Laird, 1983, 2006; Lakoff, 1987; Laszlo, 2015; Liu et al., 2015; Nagel, 1979; Reif & Larkin, 1991; Rodriguez, 2013; Vallée-Tourangeau & Vallée-Tourangeau, 2014; Wartofsky, 1968.

1.3 Systemic student profile

Figure 2. 4P profile.

Systemic education brings about learners with systemic profiles that embody professionals' patterns of success in modern life and that have at least four major general traits in common that would qualify them as 4P profiles. A 4P profile is the dynamic, constantly evolving profile of a systemic, well-rounded citizen empowered for lifelong learning and success in life, and characterized with progressive mind, productive habits, profound knowledge, and principled conduct (Fig. 2). The four P's are not absolute traits of a "one-size fits all" profile. They are universal "qualifiers" for distinct individual profiles which reliable research in cognitive science has constantly proven to be necessary for success – and excellence – in any aspect of life and in any era, especially our modern era (Halloun, 2017a, 2019).

Progressive mind refers to an overall systemic and dynamic mindset with clear vision and determination to empower oneself and others for continuous growth and enhancement of various aspects of life.

Productive habits refer to practical and efficient cognitive and behavioral habits that are prone to systematic improvement and creative and advantageous deployment in various aspects of life.

Profound knowledge refers to a sound, essential, and coherent corpus of knowledge that readily lends itself to continuous development and efficacious and efficient deployment in various aspects of life.

Principled conduct refers to productive and constructive conduct in all aspects of life, while intuitively driven for excellence and guided by a widely and duly acclaimed value system.

Under SCE, science courses of any level contribute to the development of a student's 4P profile through engagement in structured transactions with physical realities that involve the construction and deployment of scientific models with appropriate systemic tools and following systemic rules of engagement.

Systemism predominates in science where the construction and deployment of scientific models in the context of appropriate theory and paradigm are the prime systemic processes in all sorts of transaction with the physical world. As discussed in § 4, a scientific model is a conceptual system, a system conceived by human minds in a readily communicable fashion, and mapped onto particular aspects of physical realities manifesting a particular pattern. Science education is thus most propitious for, and should therefore be particularly concerned with, helping students of all levels develop, and live by, such model-based systemic worldview.

2. Systemic transaction with physical realities

Science helps us systematize our transaction with the real world (Fig. 1). More specifically, it helps us systematize how we go about:

1. exploring existing physical realities, i.e., describing and explaining their state (or change of state);

2. organizing subsequent knowledge about such realities into scientific theory and paradigm, a paradigm being a coherent set of complementary theories governed by common metaphysical tenets and constructed and deployed in accordance with similar rules;
3. deploying scientific knowledge efficiently for various purposes, including but not limited to tracking the history or evolution of existing physical realities and predicting their future, controlling and changing their current and future state, discovering new physical realities in the universe, and inventing novel realities including, but not limited to, technological artifacts.

Systematization of our transaction with the physical world begins by imposing order in this world from both ontological and epistemological perspectives. From an ontological perspective, scientists concentrate on universal patterns. From an epistemological perspective, scientists represent, in specific respects of interest, various physical systems manifesting a particular pattern with a single scientific model in the context of an appropriate scientific theory (Fig. 3).

2.1. Patterns and models

Patterns predominate in the universe at all levels, from the subatomic scale to the galactic scale, including the human mind, brain, and body. Patterns, like those in the structure of atoms and solar systems or the day-and-night and seasons cycles on Earth, are morphological (structural) or phenomenological (behavioral) regularities across space and time in the state of physical realities of all sorts and scale. Patterns predominate in our thoughts and memories as well, and mental patterns are crucial for sustaining knowledge in our long term memory. We also have a natural tendency to look for patterns in the world around us, and even to rationally impose patterns on what we perceive in this world or conceive about it (Halloun, 2017a, 2019).

Physical patterns are best revealed through *systemism*, i.e., a systemic worldview whereby we look at physical realities not individually and in isolation from each other, but in relation to each other in well-delineated physical systems (*ibid*). Simply put, and as discussed in § 2.2 and further elaborated in § 3.1, a physical system is a set of physical entities (objects and their properties) that interact with each other, or that are connected or related to each other, in isolation from other entities, or in connection to certain surrounding entities that make up the environment of the system. Various entities interact to maintain the system as a whole in a given state and allow it to serve a specific function, operate in specific modes, and bring about a specific output.

As indicated in Figure 3 and discussed in § 3.2, a scientific model is a conceptual system, a humanly conceived abstract system, that corresponds to, or that is mapped onto, only those

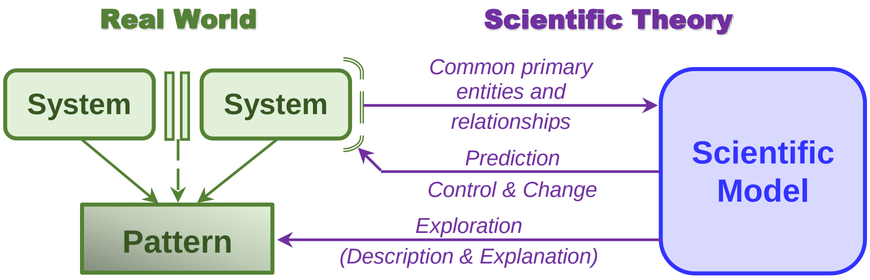

Figure 3. Systemic transaction through a scientific model (conceptual image) with many physical systems manifesting a particular pattern.

primary interacting physical entities and mutual interactions (or connections or relationships) that are common to all physical systems and that are significant to the pattern of interest. The conceptual model may eventually be reified into a physical model, i.e., a physical system consisting of physical entities similar to or representing only the primary entities considered in the model referents, i.e., in the physical systems manifesting the pattern in question.

Every scientific theory provides principles and other premises for various modeling processes the most important of which are the construction, corroboration, and deployment of a particular set of scientific models. Each model is constructed with the exclusive function of describing and/or explaining, in specific respects and to a certain level of approximation or precision, a particular pattern in the real world. Like any conceptual image, the model is constantly evaluated and regulated (Fig. 1). The model is evaluated primarily by deploying it for the prediction of specific aspects which its function is about in the state (or change of state) of its referents (Fig. 3). It is corroborated, and thus inducted in the corresponding scientific theory, if it allows good predictions at the set level of precision. Otherwise, the model is regulated (modified or replaced altogether) and then evaluated as before. Once induction achieved, the model may be used for the control and change of its referents, and the discovery and invention of entirely new referents. It continues to be evaluated and regulated in the process.

2.2. System delineation

A scientific model is a conceptual image that represents in specific respects many physical systems manifesting a specific pattern (Figs. 1 and 3). Figure 4 shows how we may delineate a physical system by convenience, i.e., how we may set its boundaries with its environment, if any, in order to best reveal the pattern of interest or any other system function, operation, and output we might be interested in (Halloun, 2004/6, 2007). For the purpose of model construction, the boundaries are set to account exclusively for certain entities (objects and their properties) and interactions (or connections or relationships) among entities. These are *primary* entities and interactions. They set the state of interest of any given system or the common state of many systems that reveals the pattern which the scientific model is supposed to describe and/or explain. Primary entities and interactions are distinguished from their *secondary* counterparts that are ignored in model construction. Secondary entities and interactions are actually part of the physical makeup of any system and its environment. They are ignored in model construction because they do not contribute significantly to the system state of interest, and particularly not to pattern description and explanation.

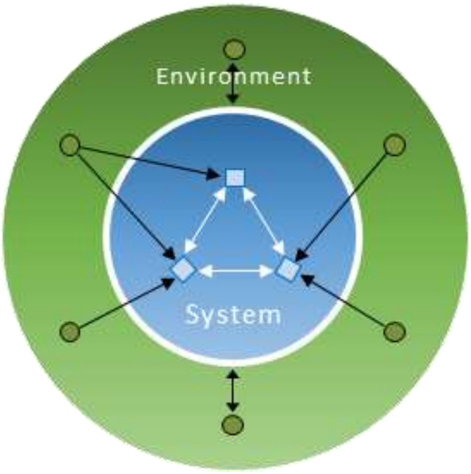

Figure 4. System delineation for model construction.

Boundaries are set sometimes so that the system consists of a single entity within a particular environment, if any. The system is then called a *simple* system, and so is the model that represents it. Otherwise, boundaries may be set to enclose all entities of interest inside the system and end up with an *isolated* system of no environment to consider. At all times in model construction, we are exclusively interested in specific primary interactions. Three instances of primary interactions that are typically considered in scientific models are depicted in Figure 4.

The two-sided arrows in Figure 4 between system *constituents* (entities inside the system depicted with squares) indicate an interest in *mutual inter*actions between connected entities. The one-sided arrows between certain *agents* in the environment (entities outside the system depicted with disks) and constituents of the system indicate an interest only in the *action of* those agents on designated constituents, but not in the reciprocal action (sometimes called reaction) of system constituents on agents. The two-sided arrows between the system boundaries and agents in the environment indicate an interest in certain *mutual inter*actions between connected agents and the system as a *whole*, thus in the synergetic impact on the environment of all system constituents acting together, and not the impact of individual constituents.

SCE provides appropriate tools to systematize how we may define systems of all sorts and deploy them in appropriate educational settings. In particular, it provides for transposing scientific models from tools of scientists' transaction with the real world into efficient pedagogical tools for meaningful and productive learning of science. This is what our attention is turned to in the rest of this article.

3. System schema and taxonomy of learning outcomes

A system has been defined in a variety of ways in the literature, but they all converge on the idea that a system may consist of one entity (if simple) or many interacting or connected entities (if compound) confined within well-defined boundaries to serve particular purposes. The constituent entities, and thus the system, may be either physical, if consisting of material objects, or conceptual, if consisting of humanly conceived and communicable abstract elements like in the case of scientific models.

We define a system of any sort, in both the physical world and the conceptual realm of human knowledge, in accordance with a four-dimensional schema (Fig. 5) that specifies the system's scope, constitution, and performance in the context of an appropriate framework (Halloun, 2011, 2017a, 2019). The schema may be used for both scientific and pedagogical purposes. In the latter respect, a system of any sort may be defined along the four dimensions of the schema in the form of learning outcomes spelled out in accordance with SCE taxonomy of such outcomes.

3.1. System schema

The system schema serves as a template for the construction of any system, scientific models included. It is also a tool for all sorts of systemic applications in education, from the design of a curriculum and curriculum materials, textbooks authoring included, to the use of models in class as pedagogical tools. The four dimensions of the schema, framework, scope, constitution, and performance, are outlined here for any system. The use of the schema in the construction of scientific models in science courses is discussed and illustrated in the following section.

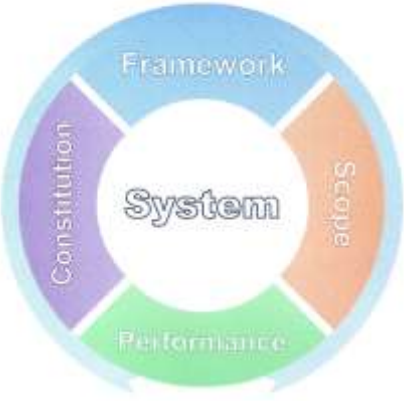

Figure 5. System schema.

1. The *framework* of a system consists of all: (a) theoretical premises, like assumptions, principles, value system, and other ontological, epistemological, methodological, and axiological maxims and provisions typically spelled out in the paradigm of a professional

community, and (b) ensuing strategic choices, which, along with theoretical premises, guide the specification and reification of the scope, constitution, and performance of a system.

2. The *scope* of the system specifies:
   a. the system *domain*, or the field or area in which it exists and is of importance;
   b. the system *function*, or the specific purposes it is meant to serve in that domain.
3. The *constitution* of the system specifies:
   a. the system *composition*, i.e., its primary constituents that may be physical or conceptual entities (objects and their primary individual properties) inside the system, and that are relevant to its function, as opposed to secondary entities that may actually be part of the system but that may be ignored because we deem them irrelevant to the system function;
   b. the system *structure*, i.e., primary connections (interactions or relationships) among primary constituents that determine how the system serves its function;
   c. the system *environment*, i.e., its primary agents or primary physical or conceptual entities outside the system, other systems included, along with their primary individual properties, that may significantly affect the system structure and function;
   d. the system *ecology*, i.e., primary connections (interactions or relationships) between individual primary agents and constituents, and/or between the system as a whole and its environment, that significantly affect how the system serves its function (and affects the environment, if we are interested in the mutual system-environment impact).

   It is worth stressing here that, for pedagogical purposes discussed elsewhere (Halloun, 2001, 2004/6), the composition and environment facets of the constitution dimension only list system constituents and agents, and do not establish connections among them. The latter are the object of the structure and ecology facets.
4. The *performance* of the system specifies:
   a. the system *processes*, i.e., dynamical actions (operations, mechanisms, or maneuvers) which constituents, and/or the system as a whole, might be engaged in, on their own (isolated system) and/or under external influence (of the environment), in order to serve the function of the system following specific rules of engagement;
   b. the system *output*, i.e., products, events, or any other effect (services included, when the system is, say, of social or industrial nature) that the system actually brings about, on its own or in concert with other systems as a consequence of its ecological interactions and processes, and that may fall within or beyond the scope originally set for the system.

3.2. Taxonomy of learning outcomes

For pedagogical purposes, a system, and particularly a scientific model, is specified under SCE in the form of *expected* learning outcomes along the four dimensions of the system schema. A *learning outcome* is a unique bit of content or process knowledge, or of any other related state of mind, that a student has actually achieved, at the cognitive or behavioral levels, and sustained in memory about a particular schematic aspect of a particular scientific model or any other object of learning, or about an aspect common to a variety of such models or objects. Learning outcomes come in four types or categories distinguished in the four-dimensional SCE taxonomy: epistemic, rational, sensory-motor, or affective. Each dimension of the taxonomy, or each type or category of learning outcomes, is further classified into a number of *facets* or subcategories that may be specific to a particular field or common to many fields (Halloun, 2017b).

Epistemic learning outcomes pertain to various types of *conceptions* of content knowledge. Conceptions include concepts, laws, theorems, and other abstract constructs conceived to distinguish a particular entity from other entities in the physical world or the mental realm, or to describe or explain common morphological or phenomenological aspects of various entities. Each conception may be further classified into a number of subcategories. For example, scientific laws may be classified into state, composition, interaction, causal, and quantification laws.

Rational learning outcomes pertain to various types of *reasoning skills* of process knowledge. A reasoning skill may be, among others, of analytical, criterial, relational, critical, or logical type. Each reasoning skill may be further classified into a number of subcategories. For example, analytical reasoning skills in science comprise, among others, surveying, differentiating, identifying regularities, describing, explaining, predicting.

Sensory-motor learning outcomes pertain to various types of perceptual and motor skills, or *dexterities* of process knowledge. Dexterities may be, among others, of communication, digital, manipulative, artistic, or eco-engagement type. Each dexterity may be further classified into a number of subcategories. For example, communication dexterities in science comprise, in addition to the generic listening, reading, speaking, writing, and coordination of multiple representations distinguished in other fields, the specific dexterities of producing and manipulating a variety of mathematical representations on paper and digital platforms.

Affective learning outcomes pertain to various types of *affects* especially those that significantly affect student achievement in education. Those affects include, among others emotions, motives, interests, dispositions, and values. Each affect may be further classified into a number of subcategories. For example, dispositions in any field comprise open-mindedness, risk taking, autonomy, curiosity, and creativity.

Learning outcomes along some or all four dimensions may come together in systemic clusters of specific functions like metacognitive controls and competencies. *Metacognitive controls* include reasoning skills and affects that monitor and regulate our thoughts and actions, and especially memory formation and retrieval. A *competency* is a specific or generic cluster of all four types of learning outcomes. A *specific* competency helps achieving a specific task like solving a specific problem about a particular system or situation. A *generic* competency allows the deployment of attained learning outcomes in novel situations and in the development of new learning outcomes and subsequently new competencies (Halloun, 2017b).

4. Model construction

Simply put, a scientific model is the representation, in specific respects and to a certain extent, of a morphological and/or phenomenological pattern in the real world, i.e., a pattern in the structure and/or behavior of physical systems. According to the system schema (Fig. 5 and § 3.1), every model is constructed in the *framework* of an appropriate scientific theory to serve a specific function about the pattern in question and the physical systems manifesting the pattern.

A scientific theory, like the Newtonian theory of classical mechanics, is a conceptual system set in the framework of a given scientific paradigm for modeling inquiry. It consists of generic rules, laws, and other theoretical statements for the construction, corroboration, and deployment of a particular family of models, and provides a repository for such models. For instance, the Newtonian theory in question provides for putting together and processing a family of particle models for the description and explanation under certain conditions of physical objects in specific types of translational motion. This section outlines how we go about setting the function of a scientific model as part of its scope, and determining its necessary constitution and performance.

4.1. Scope

Physical systems manifesting the pattern represented by a scientific model are the model *referents* and make up its *domain*. As mentioned before, the main *function* of a scientific model is the description and/or explanation of the pattern it represents, and thus of its referents in certain respects. The model also serves to: (a) track the history of these referents and predict their future in the same respects, (b) control and change the current and future morphological and/or phenomenological state of these referents, (c) discover new referents, and (d) create or invent new physical or conceptual referents.

The scope of any scientific model is defined under specific physical and theoretical conditions, and to a certain degree of precision and with certain limits of approximation. Two different scientific models may not have exactly the same scope. They may have the same domain, but not the same function. Take for example the case of physical objects undergoing translation and rotation (or spin) at the same time. When the speeds of such objects are relatively small by comparison to the speed of light, their translation may be satisfactorily described, explained, and predicted with particle models in the framework of Newtonian theory, whereas their rotation may be similarly explored with particular rigid body models in the framework of Euler theory. Neither theory nor corresponding models would be valid when exploring physical objects moving at relatively high speeds and/or when high levels of precision are needed.

4.2. Constitution

The *composition* of a scientific model consists of object and property *concepts* that represent respectively the primary physical objects and their individual properties that are repeatedly detected in the makeup of all physical systems in the model domain (model referents) and that are pertinent to the model function (Fig. 4). These concepts are defined and related to each other in an appropriate reference system. Mutual relationships that set the model *structure* are spelled out in the form of appropriate laws, principles, and other theoretical statements provided by the chosen scientific theory.

A model constitution is only about morphological aspects of model referents, mainly the internal composition structure of these referents, and not phenomenological aspects like the state or change of state of motion. The latter make the object of the model performance. Relationships of interest in model structure thus pertain to the shape of individual objects if necessary, the configuration or topology (relative position) of various objects, and interactions between objects that maintain or change such topology. Newton’s law of universal gravitation is an in instance of interaction laws in classical mechanics.

A model is simple when it consists of a single object concept, and compound or composite otherwise. In the formal case, the model would have no structure. In most science courses, especially introductory courses, simple models are the most efficient pedagogical vehicles for meaningful understanding of scientific theory. This is the case, for example, of particle models in Newtonian classical mechanics whereby it is often convenient to consider and model physical objects in translation one at a time (simple systems), and study the interaction of individual objects with other bodies by situating all those bodies in their environment. The latter bodies would then be treated as agents whose action on any given object, but not the reciprocal object reaction, is only taken into consideration in the model.

In addition to object and property concepts representing common primary constituents of physical referents, model constitution also includes similar concepts representing common primary entities (agents and their properties) in the referents' *environments* (Fig. 4). Relationships of interest that make up the model *ecology* are then spelled out between various concepts, in the same reference system, with appropriate topology and interaction laws, and related theoretical statements provided by the same scientific theory.

4.3. Performance

The constitution dimension is primarily concerned with morphological aspects of models and other systems. In contrast, the performance dimension is concerned with phenomenological aspects (or operations in pure mathematical models). *Processes* that a scientific model may be about pertain to the dynamic state of its referents and allow the description and explanation of the respective *output*, this being any event, or the lack of it in static states, in which may be involved any primary object inside model referents or any individual referent as a whole.

State laws, like the laws of motion in kinematics (often called equations of motion in physics textbooks), and related theoretical statements are then considered to describe events in question, on the one hand. On the other, causal laws, like conservation laws, the work-energy principle, and Newton's second law in classical dynamics, are considered to explain the conservation or any possible change in the state of events.

Mastering the exploration function (description and explanation) of a scientific model is very critical for meaningful understanding of the model and appreciation of its utility in the real world. However, the model gains its full significance beyond referents' exploration, i.e., when deployed for the prediction, control, and change of the state of existing physical referents, and especially for the discovery of new physical referents and the creation of novel conceptual or physical referents. Because of practical constraints, the latter functions are rarely addressed in traditional science courses. Students are thus left unable to realize and appreciate all the functions that scientific models can serve. Such constraints need to be overcome – and they can be, to a certain extent, with the use of simulations and other affordable technology – so that students can take advantage of science in systematizing their transaction with the physical world beyond exploration purposes.

For efficiency and objectivity purposes, various model conceptions (concepts and relationships among concepts) are often mathematically expressed in science, especially in model constitution and performance. Corresponding semantic and syntactic rules need then to be specified explicitly for students to make sense of mathematical symbols, expressions, and depictions by correspondence to the model referents, and to use various mathematical representations and operations successfully in model construction and deployment.

The use of the system schema in the construction of scientific models is illustrated in Table 1 with the case of Bohr's model of hydrogen like atoms. The table provides sample epistemic and rational aspects of the model that are typical of introductory college physics (and chemistry) courses. The reader can easily realize that epistemic cells include particular information or theoretical statements about Bohr's model that the student is expected to "*have*" at a given point of instruction, while rational cells include what the student is expected to "*be*" capable of doing for the construction and subsequent deployment of the model in question. For practical purposes, including lesson planning and implementation, information provided in each cell needs to be translated into suitable learning outcomes in accordance with SCE taxonomy as described elsewhere (Halloun, 2017b).

Table 1

Partial outline of Bohr’s model of the atom in accordance with the system schema for introductory physics (and chemistry) courses

Schematic dimension / facet		**Sample epistemic aspects**	**Sample rational aspects***
Framework		Bohr’s atomic theory: A mix of classical theory and old quantum theory. The former includes Newtonian theory of mechanics and select aspects of the classical electromagnetic theory (namely Coulomb’s electrostatic interaction but not the radiant energy emitted by accelerated particles). The latter theory works in certain respects in contradiction with Schroedinger’s quantum theory (e.g., it assumes that electrons move in well-defined orbits), yet it works well to a very good approximation with the model referents.	Critical reasoning by virtue of which the validity of classical theory is established for studying referent atoms in their stable states (mainly because the orbital speed of the electron is about 1% that of light for small Z), and of the alternative quantum theory for changing states. Logical reasoning whereby it is understood that: (a) ignoring certain aspects of classical electrostatics and modern quantum theory yields reasonable predictions for concerned atoms, and that (b) the predictions of classical and quantum theories should correspond to each other under certain constraints in accordance with Bohr’s correspondence principle.
Scope	**Domain**	Hydrogen atom (H) and one-electron (hydrogen-like or hydrogenic) atoms/ ions with small Z. Model referents also include, though not to as good an approximation, alkali elements (Li, Na, K, Rb, Cs, Fr) in the same group with H. The model applies throughout the universe that consists mostly of isolated hydrogen atoms.	Criterial and analytical reasoning whereby a pattern is defined among hydrogenic atom/ions that may be classified together and distinguished from many-electrons atoms or ions and even one-electron ions with large Z. Critical and relational reasoning to appreciate the model’s significance/ reference class at the universal scale.
	Function	Description and explanation of certain but not other aspects of a single electron bound to a significantly heavier nucleus (with small Z) on an assumed circular orbit, whether in a stable state or making discrete transition to certain other orbits of limited energy levels.	Logical and critical reasoning to specify which questions the Bohr model may answer to certain limits about hydrogenic atom/ions, and which not (e.g., explaining the fine spectrum structure on elliptical orbits requires Sommerfeld’s model instead). Analytical reasoning to set how the model can describe and explain structural and behavioral aspects in its domain about hydrogenic atom/ions.
Constitution	**Composition**	A nucleus with one proton (hydrogen atom) or more (hydrogenic ions with small Z), and a single electron for hydrogen-like atoms. Properties of interest include mass and quantized charge of the considered particles, as well as energy mostly of the electron.	Analytical reasoning by virtue of which only primary entities (electron and nucleus) and properties are included in the model, and other (secondary) entities and properties left out. Criterial reasoning to specify the characteristics of elementary particles, namely here those of the electron and the quarks making up the proton.

Schematic dimension / facet		**Sample epistemic aspects**	**Sample rational aspects***
Constitution	**Structure**	Classical interaction between the nucleus and the electron partially represented by a central (binding) Coulomb force, under the assumption of a fixed nucleus with a mass of about 2,000 times that of the electron and a concentration of all positive charge. Despite its acceleration, the electron does not radiate electromagnetic energy, and its total energy remains constant on stable orbits, the most stable orbit being at the ground level (energy level 1, energy value -13.6 eV). The total energy of the electron is quantized in line with the quantization of its orbital angular momentum.	Relational reasoning to connect various primary entities distinguished in the model composition and environment. Connections are established with classical and quantum laws and other theoretical statements properly chosen through critical reasoning. They include: (a) interaction and causal laws that set model constitution; (b) causal and state laws that set model performance. Criterial reasoning to: (a) establish structure and ecology, say by analogy to other models (e.g., to planetary models in the context of classical Newtonian theory); (b) extrapolate the universality in the expression of certain laws at all scales (e.g., inverse square laws in gravitational and electrostatic interactions); (c) compare the relative magnitude of involved interactions, and, say, decide –with critical reasoning– which one can be ignored (primarily the gravitational interaction between the electron and the nucleus). Relational reasoning (along with communication dexterities) to establish semantic and syntactic correspondence between, and among, different mathematical representations and the physical objects, properties, and relationships they represent in the studied atoms.
	Environment	Isolated atom with no environment to consider when in stable condition, especially at the ground level. Fields and neighboring atoms in the case of respectively orbit transition and atomic combinations to form molecules and other compounds and large matter structures.	
	Ecology	No ecology for the isolated atom. Interaction between a given hydrogen-like atom and other atoms it is combined with (compounds), or other types of environment (e.g., electromagnetic field).	
Performance	**Processes**	When isolated or in stable condition, mostly classical state properties and laws describing the electron's orbit around the nucleus are considered (e.g., velocity and Newtonian law of uniform circular motion). Otherwise, quantized energy levels are resorted to in the context of quantum theory.	
	Output	Matter cohesion when interacting and bound with other atoms. Energy absorption or emission when changing orbits / energy levels.	

* Reasoning skills are distinguished in this column in accordance with SCE taxonomy (Halloun, 2017b).

Because of limited space, sample concepts, laws, and other epistemic aspects are mentioned without being explicitly expressed in any form, and to avoid redundancy, sample common reasoning skills are outlined together and not separately for individual facets in the last two dimensions of constitution and performance.

5. Model organization

Every scientific model is well situated in the respective scientific theory from both scientific and cognitive perspectives. It shares certain constitution and performance aspects with other models in the theory, on the one hand. On the other, it is distinguished from other models in terms of its scope and some other constitution and performance aspects including the conceptual complexity and cognitive demands of the latter two schematic dimensions. Such organizational matters that are the object of this section must be explicitly accounted for in course materials and instruction so that students can be properly helped to come out with meaningful understanding, and empowered for creative deployment, of models and theory.

From a scientific perspective, the same concepts with the same correspondence rules to their referents in the real world enter in the makeup of various models in a given scientific theory. Furthermore, all such models share a given set of laws provided by the respective theory, typically interaction and causal laws, and are distinguished from each other by another set of laws, typically state laws. For instance, the composition of all particle models in the Newtonian theory of classical mechanics includes the same concepts of mass, charge, position, velocity, acceleration, force, work, and various types of energy. Moreover, all models in question are governed by the same universal law of gravitation as well as, among others, by the same so-called Newton's second, third, and fourth laws of dynamics. The latter three laws are respectively about cause and effect, interaction or reciprocal actions between two bodies, and composition or superposition of forces. In contrast, various Newtonian models have distinct state laws (so-called equations of motion).

From a structural complexity perspective, models are in the middle of the ontological hierarchy between concepts and theory, concepts being the least complex conceptions from a scientific perspective and the least demanding from a cognitive perspective, and theory the most complex and most demanding. Yet, and as discussed next, models are most significant for meaningful understanding of both concepts and theory from cognitive and pedagogical perspectives. Some models are though more important than others in this respect, and thus most crucial to begin with in science courses to this end and to allow students cross some critical cognitive thresholds and efficiently develop other required models in the same scientific theory.

5.1. Middle-out systemic cognition

A systemic perspective on the physical world allows us to readily grasp the big picture in a given situation, as well as the minute details in that situation, and efficiently move between big picture and details. In particular, it allows us to better understand how given physical entities interact with each other and behave to bring about certain morphological and phenomenological patterns in the universe. According to Lakoff (1987), humans organize their knowledge in middle-out structures whereby a given basic and most fundamental entity occupies the middle of the rational hierarchy between a set of entities people are familiar with and an entire corpus of knowledge pertaining to those and similar

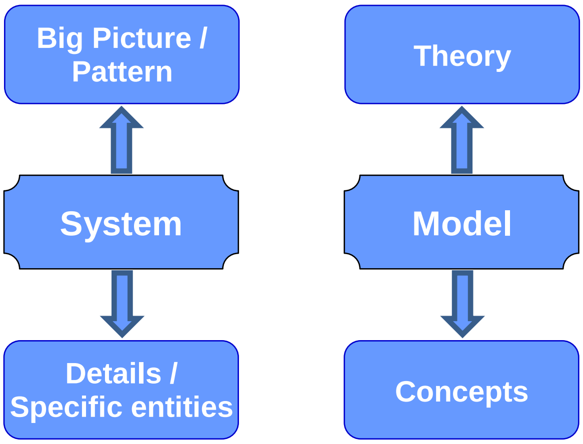

Figure 6. Systems and models in the middle-out hierarchy in the real world of physical realities and the conceptual realm of science respectively.

entities. As indicated in Figure 6, we see that such basic entity is a system when it comes to the ontology of physical realities, and a scientific model when it comes to the ontology of scientific paradigms and the epistemology of various sciences (Halloun, 2004/6, 2007, 2011, 2019).

A scientific model like Bohr's model of the atom is to theory and concept what an atom is to matter and elementary particles. The same goes for physical systems in the real world in relation to the big picture and individual details, or to a pattern and related physical entities (Fig. 6). Each elementary particle at the bottom of the structural hierarchy is essential for the structure of matter at the top of the hierarchy. However, the importance of an individual particle cannot be realized independently of that particle's interaction with other particles inside an atom. It is the atom in the middle of the hierarchy, and not elementary particles, that gives us a coherent and meaningful picture of matter, and it is the atom that best displays the role of each elementary particle in matter structure.

5.2. Critical thresholds

Scientific models in any given scientific theory (and science course) are at different levels of complexity from scientific ontological and epistemological perspectives, as well as from cognitive and pedagogical perspectives. Different models thus entail competencies and learning outcomes (§ 3.2) that impose different cognitive demands (Box 1), and may be clustered accordingly into sets of increasing complexity. At the lower end of the spectrum are models that are most critical for students to develop: (a) meaningful understanding of a given scientific theory as required in specific science courses, and (b) enough competence to start gradually relying more on their own in the learning process than on the teacher and other learning agents. Such models make up what we call the *core* part of any scientific theory and related course. At the upper end of the spectrum are *emergent* models that students may be anticipated to develop almost independently of the teacher, should they have developed all other models meaningfully.

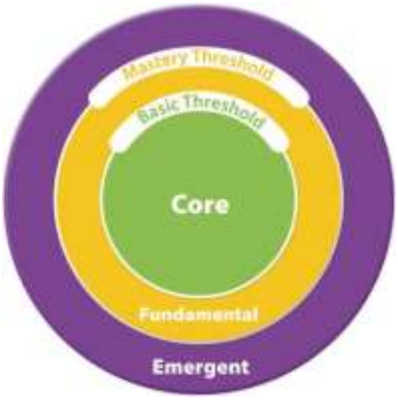

Figure 7. Critical thresholds separating sets of models of increasing level of complexity and cognitive demands in a given theory or course.

A number of *thresholds* may thus be defined to delineate the boundaries between various sets of scientific models in a given theory or science course, each set consisting of models that are almost at the same level of complexity, and thus imposing almost similar cognitive demands. Such thresholds would set: (a) an ontological and epistemological hierarchy from a

Every thought and action entail particular cognitive demands, i.e., mental efforts to engage and process certain conceptions and reasoning skills under certain metacognitive controls. Cognitive demands are primarily determined by: (a) the inherent complexity of the mental or physical task itself (including any possible communication about it), (b) the context in which the task is being carried out, and (c) the degree of familiarity with both task and context, as well as by (d) the nature and quality of resources relied upon (humans included), if any. In particular, cognitive demands of any task, like of any individual learning outcome, pertain to mental efforts required to: (a) detect and process perceived information, if any, (b) retrieve pertinent knowledge from memory, (c) negotiate between afferent data and memory, (d) construct the appropriate conceptual image (Fig. 1) to make sense of the entire experience, and (e) make necessary changes in memory. Such efforts depend primarily on: (a) the state of long-term memory, (b) the type and state of brain parts that process perceived and retrieved information, (c) the nature and extent of back-and-forth neural processes among these parts and the subsequent load on working memory, and (d) the state and efficiency of metacognitive controls engaged throughout various processes.

Box 1. Cognitive demands (Halloun, 2017b).

scientific perspective, and especially (b) a cognitive sequence that should be followed in course coverage from a pedagogical perspective. The most critical of these thresholds are the "basic threshold" and the "mastery threshold" (Fig. 7). The *basic threshold* separates core models from fundamental models (and related competencies), while the *mastery threshold* separates the latter from emergent models.

In any course, *core* scientific models are the ones that allow students to develop, in simple forms, basic and critical conceptions, reasoning skills, and dexterities (epistemic, rational, and sensory-motor learning outcomes in our taxonomy), and related specific competencies (§ 3.2) which a science course may be about. *Fundamental* models are more complex conceptual systems in the context of which students reinforce, and widen the scope of, core learning outcomes and derive from them new learning outcomes on the road toward generic competencies (§ 3.2). *Emergent* models may emerge from the composition of two or more core or fundamental models, or may be entirely new and more complex models, and require the development of generic more than specific competencies.

A student needs to meaningfully develop the *entire* set of core models before s/he can cross the basic threshold and proceed to fundamental models. Any setback in developing any learning outcome in the core set prevents the student from crossing the basic threshold, and thus from developing fundamental models meaningfully. Students normally require significant teacher assistance, as well as the assistance of other learning agents, including peers and parents, in order to reach such threshold, especially at the epistemic and rational levels. Once students cross the basic threshold, the teacher can gradually retreat from the picture until students cross the mastery threshold. Beyond the latter threshold, students should be capable of developing the more complex emergent models with the least teacher assistance ever.

For example, in some introductory college physics courses dealing with the Newtonian theory of classical mechanics, two models, the free particle model and the uniformly accelerated particle model, make up the *core* models of the theory. Two other models, the particle in uniform circular motion and the simple harmonic oscillator, may be classified as *fundamental*, and two more, the particle in uniformly accelerated motion and the particle under impulsive forces, as *emergent* models.

The two core models are most crucial for students to develop all Newtonian conceptions of translational motion, from state concepts to Newton's laws of dynamics (Halloun, 2001, 2004/6, 2007). The first model is a conceptual system that represents physical objects moving with constant velocity under no net external force. The second model is a conceptual system that represents physical objects moving with constant acceleration, i.e., with a velocity that varies with constant increments during equal time intervals. Once students meaningfully understand all Newtonian conceptions and develop sufficient competence to productively deploy these conceptions in the context of the two models in question, they reach the basic threshold and they become ready to develop increasingly more complex particle models and gradually evolve towards the mastery threshold and beyond.

In any science course, a teacher or textbook may often rely on subsidiary models to introduce students to any new scientific model. A *subsidiary model* is a particular instance of the target model which students may be familiar with, and that may facilitate the gradual development of that model. For instance, three particular cases of the uniformly accelerated particle model in Newtonian theory are usually distinguished in introductory physics courses, and each case may be introduced with a subsidiary model representing particular objects thrown near the surface of the Earth. As indicated in Table 2, the three cases are distinguished based on the initial conditions of motion (model scope), and more specifically the relative directions of two vectorial concepts: (a) the velocity ($\mathbf{v_o}$) of a particle like object at the instant one begins to explore the translational motion of the object, and (b) the net constant force (**F**) exerted on the object throughout its translation.

In certain respects, the three subsidiary models of Table 2 illustrate the increasing complexity from core to fundamental and then emergent models (Fig. 7). The top subsidiary model (particle in free fall) may somewhat be associated with core models, the middle model (particle thrown vertically upward), with fundamental models, and the bottom subsidiary model, with emergent models. In all three cases, the same Newtonian conceptions (concepts, laws, and other theoretical statements) apply, but with increasing complexity, and some conceptions are added to complement the picture as we gradually move from the core subsidiary model to the emergent subsidiary model (like the superposition principle in the latter case).

6. Model deployment

The model-based transaction of Figure 3 represents various forms of scientific inquiry with existing physical realities. Scientific inquiry is primarily modeling inquiry, or model-based inquiry. It involves systemic processing of certain scientific models, in parts or in their integrity, for the purposes mentioned at the beginning of § 2. More specifically, direct transaction with physical realities may necessitate the construction and corroboration of new model(s) in the manner discussed in § 4, or the deployment of already developed scientific models in the manner discussed in this section. When it does not involve transaction with physical realities, modeling inquiry involves processing a given model or set of models from a pure conceptual perspective, often mathematically in science and by correspondence to empirical data available on file. All sorts of modeling inquiry take place in the context of an appropriate scientific theory and involve evaluating the invoked models, regulating them, and consolidating them in the theory in question (Fig. 1).

Model deployment is about the use of a model (or set of models) for: (a) the exploration (prediction included) or transformation of existing physical realities, (b) the invention of new physical realities or artifacts, (c) the inception of new conceptions (concepts, laws, and other theoretical statements) to enhance any of the schematic dimensions of deployed models (Fig. 5), including the theory itself, and/or (d) the emergence or development of one new scientific

Table 2

Subsidiary models of the uniformly accelerated particle model in the Newtonian theory of mechanics

Initial conditions of motion	**Trajectory**	**Speed**	**Subsidiary model**
$\mathbf{v_o}$ and **F** are parallel ($\theta = 0$)	Linear	Constantly increasing	Particle in free fall
$\mathbf{v_o}$ and **F** are opposite to each other ($\theta = \pi$)	Linear	Constantly decreasing until it becomes zero at which instant the object turns back to move along the same line with increasing speed	Particle thrown vertically upwards
$\mathbf{v_o}$ and **F** make an arbitrary angle θ different from zero and π	Parabolic	Constantly increasing if θ is right or acute; constantly decreasing otherwise until it reaches a minimum non-zero value at the top of the parabola at which instant the speed starts increasing	Particle thrown at an arbitrary angle with the vertical different from zero and π

$\mathbf{v_o}$ is the initial velocity of a particle like object at the instant one begins to explore motion.
F is the net constant force exerted on the object throughout its motion.
θ is the angle $(\mathbf{v_o}, \mathbf{F})$ between $\mathbf{v_o}$ and **F**.

model or more. Model deployment may involve transaction directly with physical realities, or indirectly with corresponding data. Alternatively, it may involve processing conceptual entities pertaining to a given model and its referents. Model deployment results, at least in the mind of the person carrying out the task, in the regulation and consolidation of any deployed model, like it should always intentionally and consciously do in the mind of students studying for a particular science course.

Modeling inquiry in typical pre-college and college science courses rarely involves actual transaction with physical realities. This is understandable in many cases, especially when it comes to astronomical and subatomic realities, and even some terrestrial realities that schools and colleges cannot, and have not to, have access to. Transaction is then simulated or carried out through textbook examples that may include some photographs of such realities in addition to related information that may or may not be realistic. Whether classroom inquiry is about model construction, corroboration, or deployment, it should always be carried out according to SCE as a systemic process that involves delineating systems in provided information, representing them with appropriate models, and processing the models to bring about the desired learning outcomes (§ 3.2 and Table 1). This is true in constructing (learning) new models as well as in deploying acquired models (elaborate learning and consolidation).

Model deployment in prevailing science courses is primarily about the use of established scientific models for exploring (describing and explaining) their referents in the real world and solving related problems, on paper, in the laboratory, or in the real world of everyday life. A systemic deployment scheme is henceforth proposed for the main pedagogical purpose of helping students systematize their model-based transaction with the real world (Figs. 1 and 3), and develop some systemic habits for knowledge construction, organization, and deployment. The scheme is devised so as to contribute, in the framework of SCE, to the development of students' 4P profiles in the gradual manner described in the evolution rubric presented at the end of this section. Science teachers of all levels may readily take advantage of the proposed scheme and rubric in their courses for many purposes, but especially to help students develop systemic transaction and problem solving habits, and align course materials with students' cognitive potentials and systemically track the evolution of their profiles.

6.1. Systemic model deployment scheme

Science courses should emulate what science is about. They should primarily be about helping students systematize their systemic transaction with physical realities (Fig. 3) and their development of modeling habits, including model-based organization of scientific theory. Given the nature of conventional science courses, this can most often be achieved through the deployment of established scientific models, *especially in problem solving*, for the purpose of learning what these models are about according to the system schema of Figure 5 as well as for the development of the systemic habits in question.

Model deployment, and especially traditional problem solving, is then basically about model "adduction" and processing in the context of an appropriate scientific theory to serve specific purposes, including conventional problem solving. It can take place in science courses somewhat in the manner scientists carry it out as shown in Figure 8. While being constantly evaluated and regulated, model deployment goes consecutively in seven non-linear phases beginning with systemic analysis of a given situation and ending with model consolidation.

Systemic analysis is about analyzing the situation at hand in order to: (a) identify the appropriate scientific theory in the context of which all phases need to be carried out, including the

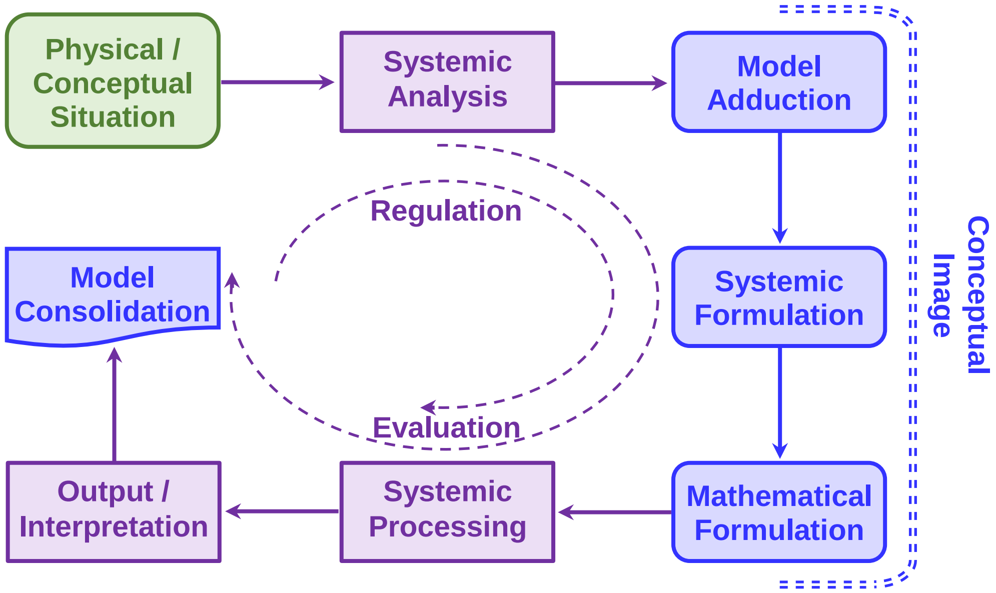

Figure 8. Systemic model deployment, problem solving included.

analysis itself, (b) tease out primary from secondary entities (objects and properties, physical and/or conceptual), and (c) group together entities that belong together in one system or more (Fig. 4).

Model adduction is about choosing the appropriate model(s) that best represent the delineated systems from the repertoire of models in the chosen theory. This choice is implied primarily by the scope of each model (Fig. 5).

Systemic formulation is about the choice from the constitution and performance dimensions of each model (Fig. 5 and Table 1) of appropriate conceptions (concepts, laws and other theoretical statements) that represent best the selected primary entities and relationships among them in the make-up of a given system. Systemic formulation may involve making certain assumptions about primary entities and relationships. It takes place in an appropriate reference system.

Mathematical formulation is about the depiction of chosen conceptions and statements made before with appropriate mathematical representations (algebraic symbols and equations, geometric icons and diagrams, graphical representations, etc.) and turning the adduced scientific model(s) into mathematical model(s).

Systemic processing is about analyzing and running the model(s) formulated so far (the *conceptual image* constructed in the prior three phases) in order to serve the purposes of model deployment.

Output and interpretation is about reaching the desired results (e.g., solution to a given problem and answers to certain questions), interpreting the results for the originally set purposes and extrapolating them beyond these purposes to regulate deployed model(s) in any of the four schematic dimensions (Fig. 5).

Model consolidation is about integrating the regulated model, along with all learned lessons, with prior knowledge and especially with other models in the same scientific theory, and with related learning outcomes and competencies already in memory.

The model deployment scheme is sequential in the sense that no phase can be reached without going through prior phases. The scheme is though non-linear in at least two respects. First, some phases, like systemic and mathematical formulation, may be carried out concurrently. Second, and as evaluation may deem it necessary, one may at any time go back to previous phases and reiterate the process from where it was retaken in order to regulate the work carried out so far partly or entirely as indicated by the dashed curved arrows in Figure 8.

6.2. Model deployment as model construction in systemic learning cycles

The same scheme of Figure 8 may be adapted to model construction, i.e., to helping students construct, in accordance with the system schema of Figure 5, a new scientific model that they have not encountered before. The only major change would be in phase 2 of the scheme where model adduction would not consist of bringing in an appropriate scientific model from the student repertoire of models. Instead, and subsequent to the systemic analysis phase that would show that no model in the repertoire in question is appropriate for the situation at hand, students would be guided to realize that the situation in question corresponds to a new pattern that requires the construction of an entirely new model in the context of the appropriate scientific theory. The same approach would be followed when students are guided to transform a subsidiary model into a more comprehensive model, or even to develop any aspect still missing in a model constructed before.

Model deployment is carried out under SCE as an integral part of model construction, or simply as model construction, and not as an instructional phase that follows, or that follows from, model construction. Under conventional instruction of lecture and demonstration, and following Bloom's taxonomy of educational objectives and some learning cycles proposed in the literature, certain conceptions are first introduced by the teacher and subsequently "applied" and then deployed in the larger sense. Bloom's pedagogical philosophy assumes that "knowledge" and "comprehension" of course materials precedes "application" of such materials in simple situations and subsequent more involved deployment requiring "higher order thinking skills", namely analysis, synthesis, and evaluation or creativity (Anderson et al., 2001; Bloom, 1956). Notwithstanding the fact that Bloom's hierarchy of educational objectives is flawed (Halloun, 2017b), according to SCE, model deployment should not be distinguished from model construction, at least not in science courses where model deployment is restricted to exploratory tasks of description and explanation, and prediction of the state of certain entities. Every model deployment task is a task of continuous model regulation, elaboration, and consolidation. Elaboration is about the development of new aspects in any schematic dimension of the model, from scope to constitution and performance, and even the scientific theory in the framework of which all modeling tasks are carried out.

Model deployment "as" model construction is systematically carried out in systemic learning cycles described elsewhere (Halloun, 2001, 2004/6, 2007). A *systemic learning cycle* in science courses is an experiential modeling cycle carried out in line with the scheme of Figure 8. Each cycle is devoted to the comprehensive construction (deployment included) of a given scientific model in accordance with the system schema of Figure 5. The cycle is experiential in the sense that it continuously involves direct or indirect transaction with physical referents of the model (Halloun, 2017a, 2019), at least until students become capable of taking the model to new horizons in disconnection with the physical world. A cycle begins with relatively simple experiential tasks. It is reiterated, as often as necessary, with tasks of increasing complexity in line with the natural evolution a learner goes through in developing any learning outcome, competency, or profile trait as discussed next.

6.3. Evolution rubric

Model construction and deployment, like any modeling inquiry task, are carried out under SCE for the ultimate goal of empowering students with 4P profiles (§ 1.3). The evolution of any profile trait, any scientific model in a student mind, and any related competency, or conception and skill, is a gradual process governed by the natural evolution of student ability to transact with physical realities (Fig. 1). The transaction with any new family of such realities, i.e., for us, with any set of systems manifesting a new pattern, is overwhelmingly perceptual and context dependent at first encounter. This imposes certain constraints on knowledge encoding and consolidation in student memory, and on subsequent knowledge accessibility and retrieval. In any science course, construction and deployment of any new scientific model should thus begin with a related subsidiary model in the context of a limited number of physical realities, preferably familiar ones, if any. As student transaction ability evolves to allow referent diversification and context-free modeling processes, modeling inquiry with the same pattern and model can then gradually evolve to encompass more and more novel physical referents, and transform the subsidiary model of limited scope, constitution, and performance, into the target model with the full fledge schematic dimensions (Fig. 5).

Five evolution stages are distinguished in SCE in terms of a number of parameters including the scope of transactions with physical realities in the context of which any profile trait or learning outcome pertaining to a given model or set of models is developed. Other parameters include: (a) the level of autonomy or, alternatively, of dependence on learning agents and physical resources in carrying out transactions in question and various modeling inquiry tasks, (b) the level of engagement and leadership in working with others, and (c) metacognitive controls especially those of motivation and self-satisfaction (Halloun, 2017b).

The five stages are labelled respectively as stages of initiation, inception, emulation, production, and invention. The first three stages are heavily contextual, and students need to go through with learning tasks (transactions) that impose relatively low-level cognitive demands below those that characterize the basic threshold of Figure 7. Student success in model construction and deployment is: (a) relatively low and restricted to narrow contexts in the first stage of *initiation*, (b) partial in the second stage of *inception*, and limited to some familiar situations, and (c) satisfactory in the third stage of *emulation*, but only in familiar physical contexts. The last two stages of *production* and *invention* are increasingly open to novel situations, including context-independent ones, and students can go through with learning tasks that impose cognitive demands above the basic threshold at first, and then, gradually, at and beyond the mastery threshold of Figure 7.

A student ability to carry out each of the seven phases of the modeling scheme of Figure 8 evolves through the five stages mentioned above. The evolution is gradual and not comprehensive at any stage. Furthermore, a student does not necessarily evolve to the same stage across all seven phases of the scheme, and is thus not necessarily capable of carrying out all these phases at the same cognitive level (evolution stage) in any modeling task. Table 3 presents some characteristics of each phase of the seven phases in model deployment in each of the five evolution stages. One can readily notice that a student might be at one particular evolution stage in a given deployment phase and lags one stage behind or be one stage ahead in another phase.

Table 3

Evolution rubric for various phases of model deployment

Stage	5 (Invention)	4 (Production)	3 (Emulation)	2 (Inception)	1 (Initiation)
Achievement **Phase**	Design and reification of novel systems; transformation and creative exploration of existing systems.	Transformation (change / control) and creative exploration of existing familiar and unfamiliar systems.	Exploration (description, explanation) & prediction (but not transformation) of existing familiar (but not unfamiliar) systems.	Limited exploration of existing familiar systems.	Partial success in the exploration of a few existing familiar systems.
Systemic Analysis	Comprehensive delineation of any system with primary entities and necessary assumptions in an appropriate reference system under the appropriate framework.	Comprehensive delineation of any system with primary entities and necessary assumptions in an appropriate reference system under the appropriate framework.	Comprehensive delineation of familiar (but not unfamiliar) systems with primary entities and necessary assumptions in an appropriate reference system under the appropriate framework.	Delineation of some but not all familiar systems, and delineation of others with superfluous or wrong details, in perhaps an appropriate reference system under the appropriate framework.	Wrong or partial system delineation with superfluous or wrong details, in an (in)appropriate reference system under the (in)appropriate framework.
Model Adduction	Correct choice of the appropriate model(s) and necessary conceptions, and invention of new ones, with necessary theoretical premises.	Correct choice of the appropriate model(s) and formulation of necessary theoretical premises.	Correct choice of the appropriate model(s) and formulation of necessary theoretical premises, often with familiar (but not with unfamiliar) systems.	Correct choice of the appropriate model(s) in limited instances with possible lack of necessary theoretical premises.	Bad choice or lack of some of the appropriate model(s) and lack of necessary theoretical premises.
Systemic Formulation	Comprehensive and correct choice or invention of all necessary conceptions (concepts, laws, etc.) with proper correspondence to referents and among conceptions.	Comprehensive and correct choice of all necessary conceptions (concepts, laws, etc.) with proper correspondence to referents and among conceptions.	Correct choice of necessary conceptions with correspondence to referents and among conceptions, often with familiar (but not with unfamiliar) systems.	Correct choice of necessary conceptions with correspondence to referents and among conceptions limited to some familiar conceptions and systems.	Bad choice or lack of many necessary conceptions and errors in establishing proper correspondence to referents and among conceptions.

Stage **Phase**	**5**	**4**	**3**	**2**	**1**
Mathematical Formulation	Comprehensive and flawless mathematical model with convenient mathematical representation of all conceptions, and consistency among various representations.	Comprehensive and flawless mathematical model with convenient mathematical representation of all conceptions, and consistency among various representations.	Perhaps some flaws in the mathematical model and in the consistency among some representations.	Often fragmented and dissociated mathematical model with mistaken or missing representations.	Partial and fragmented mathematical model, if any, with many mistaken and inconsistent mathematical representations.
Systemic Processing	Complete, transparent, well-justified, efficacious, and efficient processing of the constructed model.	Complete, transparent, well-justified, efficacious, and efficient processing of the constructed model.	Perhaps some flaws in processing the model in certain respects.	Standing flaws in processing a mathematical model that may be originally flawed.	Vague and/or flawed processing of an originally flawed model.
Output / Interpretation	Successful transformation of existing systems and/or invention of new ones, and sound and supported output interpretation and extrapolation.	Correct results / well supported decisions, and sound and supported output interpretation and extrapolation.	Perhaps some flaws in the results / decisions, and/or the interpretation and extrapolation of the output.	Standing flaws in the results / decisions, and in output interpretation and extrapolation.	Mostly flawed, or lack of, results / decisions.
Model Consolidation	Sound synthesis of the entire experience and integration of the output with prior knowledge with necessary memory regulation.	Sound synthesis of the entire experience and integration of the output with prior knowledge with necessary memory regulation.	Perhaps some flaws in the synthesis of the entire experience, output integration with prior knowledge, and/or due regulation.	Standing flaws in the synthesis of the entire experience, output integration with prior knowledge, and/or due regulation.	Major flaws in, or lack of, synthesis and knowledge regulation.

The zigzag line between mastery Stages 4 and 5 indicates that the evolution from the former stage to the latter stage is gradual. Students in Stage 5 may stumble through sub-stages similar to Stages 2 and 3 in this table before they master the innovative function of coming up with novel systems.

In stage 3, students may be capable of successfully deploying a given model with familiar referents but not quite so with unfamiliar referents. Knowledge transfer is limited at this stage.

In stage 2, deployment is partial and limited to some, but not all, familiar situations (significantly flawed in all types of situations in stage 1), thus necessitating major remedial efforts.

Table 3 constitutes an evolution rubric that may serve many pedagogical purposes. These include lesson planning and the design of appropriate learning tasks that take students throughout any number of the five evolution stages in model construction and deployment. The rubric may also serve for the design and grading of assessment tasks, traditional problem solving included. In the latter respect, Table 3 can be readily transformed into an assessment rubric that helps grading student performance on any particular task (or of any phase of model construction or deployment) in an objective way. A student performance is then indexed at the proper evolution stage, and the appropriate regulation and/or consolidation activities may be assigned to help the student reach or reinforce the desired stage.

Assessment under SCE is a systemic endeavor that comes about as an integral part of model construction and deployment. As such, assessment turns out to be not an end by itself, but a means to a more worthy end: to systematize systemic learning of course materials and development of 4P profiles. Out of the three modalities of assessment, assessment "of" learning, assessment "for" learning, and assessment "as" learning, the last modality becomes the most important, with the first two at its service. The first modality is about ascertaining student achievement for accountability purposes, and the second, about diagnosing student knowledge state for guiding learning and instruction. Both modalities are underlined by the assumption that, in an assessment task, students retrieve ascertained knowledge from memory and reproduce it exactly as it used to be stored there. Research in neuroscience reveals that this is far from being the case, and that students actually regulate and change stored knowledge in the process of retrieving it and adapting it to the task at hand (Markant et al., 2016; Kandel et al., 2013). Assessment thus becomes an opportunity to *develop* student knowledge state, i.e., a learning opportunity; whence assessment "as" learning. Teachers may still adapt the rubric of Table 3 to their assessment "for" learning needs and use it to track and regulate the evolution of individual students' profiles, and to evaluate and efficiently regulate instructional means and practices, and the entire course ecology. Most importantly, all assessments would then be carried out as parts of an "assessment system" whereby "different types of information are collected throughout the year using a variety of assessment tools, [and] each type of information contributes to a bigger picture of student learning" (NASEM, 2017, p. 22), and each of the system components "is designed with the same set of goals in mind, even if they are used for different purposes" (*ibid*, p. 91).

7. Modeling under SCE for systemic cross-disciplinarity

Science education research has long shown that students often complete their science courses at any level, like they do in various other fields, with fragmented and compartmentalized transient knowledge that rarely makes its way to long-term memory. Knowledge fragmentation in science courses can best be resolved in systemic, model-based curricula, and knowledge compartmentalization can best be avoided when such curricula are cross-disciplinary.

Numerous efforts have been deployed lately for *convergence* of research in different academic fields and operations in industry and various other sectors of society, i.e., for removing boundaries between distinct academic and professional fields in all domains, and carrying out processes, including knowledge development and problem solving, in coherent if not similar ways. Convergence is meant to facilitate and improve the efficiency of communication, knowledge exchange, and collaboration among various professionals on issues of mutual interest, especially in those fields that were traditionally considered as remotely related, if any, like arts and sciences.

In order to systematize putting convergence into practice and bring about sustainable development at the global scale, some leading international organizations like the International Council for Science and the International Social Science Council have gone into mergers lately. According to McBean and Martinelli (2017), presidents of the two organizations in question that merged in October 2017 into the International Science Council, the merger "will provide a new institutional context for the long-called-for convergence to become a reality". It "should help foster meaningful interdisciplinarity that begins with the joint framing of problems; ensure that all disciplines are exploiting opportunities of the digital revolution, including for data integration; and unify scientific communities. It will be guided in its actions by the shared vision of advancing all sciences as a global public good".

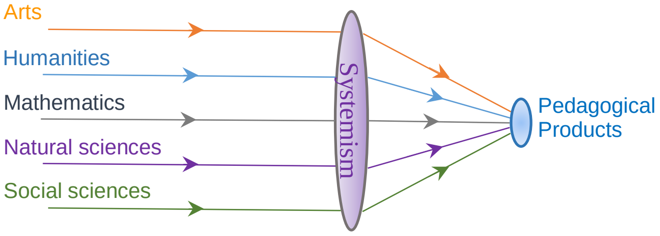

Figure 9. Systemic convergence in education to bring about pedagogical products of particular structure and function.

In education, convergence is primarily about bringing together many academic fields to come out with certain pedagogical products that may extend from the solution to a particular type of abstract or real world problems to a full-fledge curriculum (Fig. 9).

Convergence among a number of fields for any purpose, educational purposes included, can be brought about through a variety of modalities with a diversity of conceptual lenses the most meaningful and efficient of which are cross-disciplinary modalities that rely on systemic lenses. *Cross-disciplinarity* results from the integrative convergence of two or more disciplines, a discipline being here a particular branch or area in a given field (e.g., classical mechanics and relativity in physics). Different disciplines may come from the same field, but preferably from different fields (scientific and non-scientific) some of which may be non-academic fields related to any sectors of society. Professionals from various disciplines/fields (non-academic included) work collaboratively together to develop crossdisciplinary products needed within and/or outside their own professional communities, and deploy to this end a mix of already established and novel efforts. They bring together, to common facilities, their distinctive conceptual and procedural knowledge, tools, resources, etc., under an *emergent* paradigm that draws on common and concurrent aspects of their distinctive paradigms and incorporates newly agreed upon aspects. The new paradigm may sometimes *transcend* all existing paradigms and lead to the development of a brand new discipline that cuts across existing fields or that lays the ground for a completely new field. The emergent/transcendent paradigm opens the door to tackling in creative or even *innovative* ways old and new questions, problems, or issues. Crossdisciplinary products may have a mix of new and already known characteristics or entirely new characteristics (Halloun, 2018).

Cross-disciplinarity thus recognizes that no "discipline or scholarly field is an island unto itself; it is created, evolves, takes shape and responds in certain cultural, social and intellectual circumstances" (Matthews, 2012). This is especially true of scientific fields which, when considered with each other and with non-scientific fields in a systemic perspective whereby various fields are envisioned to be about a "set of theories ... unified by a philosophical framework ... that focus on the structural characteristics of systems... [we] can therefore cross the largely artificial barriers between disciplines ... [in] a cross-disciplinary approach" (Bunge, 1979, p.1).

Cross-disciplinarity is achieved in science courses when at least some scientific models are constructed with constituents coming from traditionally distinct disciplines and fields, and when these models are deployable in a variety of such disciplines and fields. Scientific fields deal with physical realities that make the object of each other disciplines and non-scientific disciplines as well. Any scientific discipline thus readily lends itself to constructing models that are cross-disciplinary in their scope, constitution, and performance (Fig. 5). This would bring coherence and consistency within and among disciplines and fields, and facilitate transfer across disciplines/fields and to everyday life.

Models and modeling in the framework of Systemic Cognition and Education helps bring epistemic coherence to students' knowledge and methodological consistency to their knowledge construction and deployment processes, within science courses and across other courses and everyday life. Such systemic pedagogy also helps students systematize their learning habits and their transaction with the real world, and come out of every learning experience with meaningful and sustainable knowledge that they can systemically deploy in creative and innovative ways outside the context of any experience in which they have been involved. Science teachers and other stakeholders are thus called upon to adopt model-based, systemic and experiential pedagogy in all their endeavors, from curriculum design to lesson planning and implementation, and from the design and management of classrooms and other facilities to the conception and use of various course materials and resources. Epistemic, rational, sensory-motor, and affective needs of individual students should be attended to in the process for lifelong learning and success in various aspects of life and not for merely passing exams of any level or scale.

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