Model-based convergence in science education in the framework of Systemic Cognition and Education

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Abstract

Convergence of episteme and skills within and with science is increasingly becoming a necessity in the workplace and many other aspects of everyday life. General education, and especially science education, must then endeavor for realistic and efficacious modalities of convergence among traditionally distinct disciplines. This may be facilitated when science curricula are model-based designed in the framework of Systemic Cognition and Education (SCE). A model, in science, is a conceptual system that represents a pattern in the structure and/or behavior of physical, real world systems, and that is constructed and deployed for various purposes, but especially for pattern description and explanation, and for exploration, transformation, and invention of physical systems. SCE is a generic pedagogical framework for coherent system-based curricula grounded in a systemic worldview that embraces patterns in human brain and mind and in the physical universe. Under SCE, barriers among traditionally distinct academic disciplines and professional fields may be circumvented for any desired level of convergence in education. This paper presents an overview of models and modeling in the framework of SCE, provides modeling tools like the system schema for model construction and a systemic scheme for model deployment, and discusses ways and advantages of model-based convergence in science education. Stakeholders may take advantage of the proposed systemic means and methods for putting together and deploying coherent model-based curricula and curriculum materials that allow for convergence within and with science education, and empower students of all levels for success in the 21st century.

Keywords

Convergence, crossdisciplinarity, evolution thresholds, learning outcomes, model, modeling, pattern, schema, system, Systemic Cognition and Education, taxonomy, transaction

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Significant paradigm shifts have taken place in the workplace and various other aspects of our daily life by the turn of the century, but not quite as significantly in education, especially science education. New professions and inventions that could not have even been foreseen in the recent past keep coming out, often as a result of convergence among traditionally distinct and even remotely related academic and professional fields. Meanwhile, our general education curricula are still being designed and deployed mostly under outdated paradigms that maintain rigid barriers among various academic fields and disciplines, and between these and vocational and technical fields, and that subsequently bring about graduates with disorderly knowledge and dysfunctional profiles. This is especially true in science education as shown by the plethora of research carried out for the past half century or so, and showing that students of all levels, and at all times up until these days, often complete and pass their science courses with fragmented, compartmentalized, and barren knowledge. To turn things around, this paper argues for model-based science education that explicitly endeavors for convergence of episteme (content knowledge) and skills within and with science under systemic pedagogical frameworks like Systemic Cognition and Education.

Major creative and innovative advances of our days did and continue to come about primarily as the result of *convergence* among many fields, i.e., as the result of bringing together professionals from different areas of expertise to work coherently together for the purpose of bringing about some products or services that could not be brought about independently by either profession. In order to systematize and optimize convergence efforts 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 inter-disciplinarity 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".

Education at all levels should come up to speed with the realities of the modern day life and empower students for smooth induction and success in the workplace and various other aspects of life (Bement, Dutta, & Patil, 2015; Brennan et al., 2014; Hart Research Associates, 2013, 2015; McKinsey, 2017, 2018, 2019; NRC, 2012a; OECD, 2013, 2016, 2018a and b; Schleicher, 2015; UN, 2015). Among other major things, education, and especially science education should allow, in practical respects related to everyday life, for convergence of episteme and skills from traditionally distinct educational fields and disciplines. Such convergence may be optimally achieved when science curricula are coherently designed under what best and most unites various scientific fields, i.e., under systemic, model-based paradigms (AAAS, 1990, 1993; Bunge, 1973, 1979; Develaki, 2006; Giere, 1992, 1994; Halloun, 2004/6, 2018a and b, 2019a; Hesse, 1970; Johnson-Laird, 1983, 2006; Nagel, 1979; NRC, 1996, 2012b; NSTA, 1995).

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 science literacy that helps people make informed decisions in all aspects of life, and, to this end, 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, 2012b; NSTA, 1995). To this end, scientific models and modeling inquiry have been constantly considered to be among the most effective pedagogical tools and processes. Such calls have been heeded and justified in the works of numerous science educators[1].

This paper promotes model-based science education in the framework of Systemic Cognition and Education (SCE) to facilitate systemic, differential convergence within and with science, i.e., systemic convergence that brings together distinct disciplines for human and ecological welfare without subduing any discipline. SCE is a generic pedagogical framework that calls for educational curricula and settings to be designed as dynamic systems the main function of which being to bring about systemic citizens empowered for lifelong learning and success in various aspects of life (Halloun, 2017, 2018b and c, 2019a and b, 2020a).

The paper comes in seven sections (§) that draw primarily on complementary works by this author on modeling theory and convergence in education (especially Halloun, 2018b and 2020b). It begins with a quick introduction of systemism and differential convergence, and follows with an overview of certain aspects of SCE that bear directly on what the paper is about, primarily systemic, model-based transactions with physical realities. 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 and model construction in accordance with the schema. Systemic model organization in particular cognitive hierarchies is discussed in the following section. Systemic model deployment following a special modeling scheme and as an integral part of model construction in systemic learning cycles makes the object of the fifth section. The following and last two sections outline respectively how differential convergence can be ultimately achieved with model-based science education and what it subsequently brings about to the advantage of students and education at large. The paper then concludes with a call for all stakeholders to adopt model-based systemic pedagogy that pursues realistic and efficacious convergence within and with science in order to empower students for self-fulfillment and success in the 21st century.

1. Systemic differential convergence in education

Numerous efforts are being deployed for convergence of research in different academic fields and of operations in industry and various other sectors of society, i.e., for crossing boundaries between distinct academic and professional fields, 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

[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.

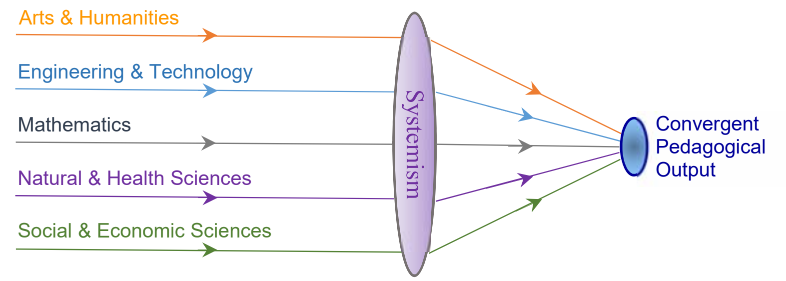

Figure 1. Systemic convergence in education to bring about pedagogical products and processes for empowering students to deal with practical aspects of life.

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 education, convergence is primarily about bringing together many academic fields to come out with certain pedagogical products and processes that may extend from the solution to a particular type of abstract or real world problems to an entirely integrated curriculum. Convergence among a number of fields for any purpose, educational purposes included, can be brought about through a variety of modalities and with a diversity of conceptual lenses the most meaningful and efficient of which, we believe, are systemic lenses (Fig. 1).

1.1 Systemism

Systemism is the worldview whereby the universe, in its integrity and its parts, is considered to consist of *systems*. Subsequently, any entity is considered to be a system or part of a system, from the atomic scale to the astronomical scale, from unicellular organisms to the most complex species, humans included, and from the physical world of perceptible matter to the conceptual realm of our human mind (Bunge, 1979, 2000; Halloun, 2019a & b, 2020a, and references therein).

Unless elementary, i.e., consisting of a single component, a system may be defined in simple terms as an ordered unity or totality of physical or conceptual elements that interact or are connected together within well-defined boundaries in order to serve specific purposes, or perform specific functions, within a given environment and under particular conditions. System properties and functions are due only in part to its individual constituents. Most importantly, a system, as a whole, has *emergent* properties and *synergetic* functions that cannot be attributed to any of its constituents independently of all other constituents (*ibid*).

Our thoughts and actions in various aspects of life, especially in formal education, are most effective when they are *systematically* carried out *systemically* in all situations, i.e., when we consistently and consciously approach any situation as being about a system or set of systems, or about a part, or parts, of system(s). Systemism offers us an exceptional framework to systematize, and infuse order in, our everlasting quest to make sense of the world around us and develop and deploy our knowledge about this world in meaningful and productive ways. It also helps us optimize our engagement with others, and bring about processes and products that none of us can produce on her/his own independently from others. Research has constantly shown that accomplished people, especially professional experts, are distinguished from other people more in how they coherently organize their knowledge than in how much knowledge they hold in mind, and more in how they systematically deploy generic skills that cut across various areas of expertise and 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 subject matters 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).

1.2 Disciplinarity and disciplinary education

General education has long been about discrete accumulation of knowledge, primarily epistemic or content knowledge, from a variety of disciplines traditionally separated by impenetrable barriers. In this paper, we use the word "discipline" to refer to traditionally distinctive academic domains like music in arts, informatics in technology, physics in natural sciences, statistics in mathematics, and finance in economic sciences. A discipline is traditionally broken down into "branches" like linguistics in the humanity discipline of language and literature, and classical mechanics in physics. In contrast, we use the world "field" to refer to a set of disciplines traditionally categorized together under labels like arts, humanities, engineering, technology, etc., and the word "realm" to put together closely related fields like arts and humanities, engineering and technology, as we did in Figure 1.

Disciplinarity, i.e., work within the confinement of a single discipline, and often within a particular "branch" in a given discipline, has long prevailed in academia and related research and development in productive sectors. Disciplinary education has then prevailed as a consequence. Disciplinary practices have always had, and will continue to have, their merits in various sectors. However, and unlike other sectors, disciplinary education has been practiced in ways that often led students to develop loose and incoherent knowledge, even within the same branch and discipline. The plethora of educational research continues to show that student disciplinary knowledge is compartmentalized to the extent that they are unable to transfer what they learn in one course to another, even in one part of a given course to another. This evidently leads to students' failure to take enough advantage of their disciplinary knowledge in everyday life and eventually in the workplace when they get there.

General education is urgently in need to follow suit with other sectors of society and tear down disciplinary barriers without entirely giving away disciplinary education, an end that is neither realistic nor necessary at least in present day. Discipline-based educational research would still be needed to help students learn disciplinary knowledge meaningfully and productively (NRC, 2012c), especially in ways to appreciate such knowledge and recognize its merits in relation of various disciplines to each other and to everyday life (NRC, 2012a). This is what we aim for by what we call "differential convergence" in education.

[2] See, for example, Assaraf & Orion, 2005; Bachelard, 1934, 1949; Bower & Morrow, 1990; Bunge, 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, 2017, 2019b; Harré, 1970; Hempel, 1965; Hesse, 1970; Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver, Marathe, & Liu, 2007; Johanessen, Olaisen, & Olsen, 1999; Johnson-Laird, 2006; Lakoff, 1987; Laszlo, 2015; Liu et al., 2015; Reif & Larkin, 1991; Rodriguez, 2013; Vallée-Tourangeau & Vallée-Tourangeau, 2014; Wartofsky, 1968.

1.3 Differential convergence

Convergence of different academic and/or professional fields (Fig. 1) is about putting together episteme and processes from different fields, in fact, select disciplines and even disciplinary branches, to answer particular questions or solve particular problems that cannot be addressed from the perspective of a single discipline. A variety of convergence modalities may then be distinguished based on the type of conceptual lenses that bring together various disciplines. More specifically, and among others, convergence modalities may be distinguished based on: (a) the framework in which a given modality is achieved, (b) how professionals from different disciplines (or disciplinary branches) work together, (c) convergence processes, (d) the extent to which different disciplines and respective paradigms preserve their identities or, alternatively, are integrated or fused together, and (e) the scope and nature of the outcomes brought about. We may subsequently distinguish five major convergence modalities: pluridisciplinarity, multidisciplinarity, interdisciplinarity, crossdisciplinarity, and transdisciplinarity. The conceptual and procedural complexity of distinguished modalities gradually increases from pluri- to trans-disciplinary modalities, and so do the extent of convergence and integration of implicated disciplines and the level of creativity and innovation in developed products (Halloun, 2018a & 2020b).

Pluridisciplinarity, at one end of the spectrum, results from the convergence without integration (synthesis) among disciplines (actually disciplinary branches) in often the same academic field. Professionals from different disciplines work separately or cooperatively together in order to develop pluridisciplinary products and processes that fulfill their own immediate needs. They do so under separate frameworks, each of which draws exclusively on the paradigm of the respective discipline in ways that preserve the integrity of the paradigm and discipline in question. Pluridisciplinary products have characteristics that are identical or similar to those of products already developed in the implicated disciplines (*ibid*).

Crossdisciplinarity and *transdisciplinarity*, at the other end of the spectrum, are the optimal convergence modalities for K-12 and higher education respectively. They both result from the integrative convergence of a number of disciplines (actually disciplinary branches) coming preferably from different fields (scientific and non-scientific), some of which may be non-academic fields related to any sector of society. Professionals from various disciplines and fields (non-academic included) work collaboratively together to develop convergence products needed within and/or outside their own professional communities, and deploy to this end a mix of already established and new or novel efforts. They bring together, to common facilities, their distinctive epistemic and procedural knowledge, tools, resources, etc., under an *emergent* framework (crossdisciplinarity) that draws on common and concurrent aspects of their distinctive paradigms and incorporates newly agreed upon aspects. The new framework may sometimes *transcend* all existing paradigms (transdisciplinarity) and possibly 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 and transcendent frameworks open the door to tackling in *creative* and *innovative* ways respectively old and entirely new questions, problems, or issues. The digital revolution of our era, the breakthroughs in neuroscience, especially cognitive neuroscience, which education may benefit of most, and the many new careers that keep emerging in the job market and that could not have been foreseen or even imagined just a decade ago, are all compelling testimonies in favor of crossdisciplinarity and transdisciplinarity (*ibid*).

Convergence, and especially crossdisciplinarity and transdisciplinarity, 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). It especially recognizes no barriers among traditionally distinct disciplines or fields within and outside academia. This is especially true of scientific disciplines which, when considered with each other and with non-scientific disciplines in a systemic perspective whereby various disciplines 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).

Convergence we are calling for in education, especially in K-12 general education and a little beyond is differential (Halloun, 2020b). It preserves disciplines with their distinctive paradigms as well as with their episteme and methodology. However, it works over and around disciplinary barriers and boundaries and allows for episteme and methodology to seep through. Differential convergence blends conceptions and processes and may integrate them to a certain level if necessary, and eventually, in higher education, to the level of bringing about emergent conceptions and processes that may transcend the original disciplines. Transdisciplinary is practically far-fetched for pre-college education, and as discussed in the last section and elsewhere (*ibid*), differential convergence in K-12 may gradually work its way through feasible modalities up to crossdisciplinarity, even if this modality may only be partially realized at the pre-college level.

Convergence in education, whether differential or not, is best achieved when various curricula are designed under systemic pedagogical frameworks. This is especially true in science education. Convergence among different branches within the same scientific discipline or from different scientific disciplines, and between these and non-scientific disciplines may be best achieved in any modality when science curricula are model-based designed and deployed, and under frameworks like Systemic Cognition and Education (SCE). Model-based science education under SCE is the object of our discussion in the following four sections (mostly reproduced from Halloun 2018b), for the purpose of achieving appropriate modalities of differential convergence at various educational levels and ultimately crossdisciplinarity in secondary education (though partially) and transdisciplinarity in tertiary education (§ 6 and 7).

2. Systemic Cognition and Education

Systemic Cognition and Education (SCE) is a generic pedagogical framework for student and teacher education 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 at any age and any educational level, and the emerging knowledge most meaningful and productive, when all entities involved, including the mind of the person engaged in the experience, are treated as interacting dynamic systems or parts of systems (Halloun, 2017, 2019a, 2019b, 2020a).

Systemic transaction with physical realities and conceptual byproducts are especially important in science education. For science is primarily concerned with the construction and deployment of scientific models (conceptual systems) that represent particular patterns in the real world, and these patterns are best revealed when the universe is looked at with a systemic worldview. Scientific models can then serve as pedagogical tools to students of all levels as

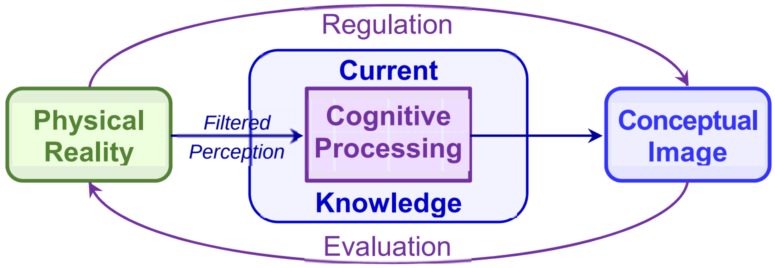

Figure 2. Human transaction with physical realities.

much as they serve as research tools to scientists, and help students like scientists build convergence bridges within scientific disciplines, and between those and non-scientific disciplines (Halloun, 2001, 2004/6, 2007, 2018b).

2.1 Systemic transaction with physical realities

Human transaction with any physical reality involves cognitive processing in the brain of select information that our senses relay to the brain about the reality (filtered perception). The process entails negotiations in the brain between filtered perception and current knowledge, and results in the formation of an *emergent conceptual image* of the physical reality that may be stored in our memory (Fig. 2). 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: (a) real afferent data from the physical reality as relayed to us by our perceptual system with (b) prior knowledge that is called upon in the memory of each of us in order to process afferent data and make sense of it.

As indicated in Figure 2, the transaction involves constant evaluation of the conceptual image and knowledge invoked from memory, and subsequent regulation of both image and knowledge. Regulation may range from simple image refinement to the construction of an completely new alternative image. It involves changes in knowledge already stored in short-term and/or long term memory, in order to accommodate image encoding, consolidation, and integration in memory (Halloun, 2017, 2018b, 2019b).

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. This includes the physical reality, the person(s) involved in the transaction and their brain(s), and the conceptual image that is most meaningful, in science and education, when conceived in the form of a scientific model (*ibid*).

Science helps us systematize our transaction with the real world (Fig. 2). 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.

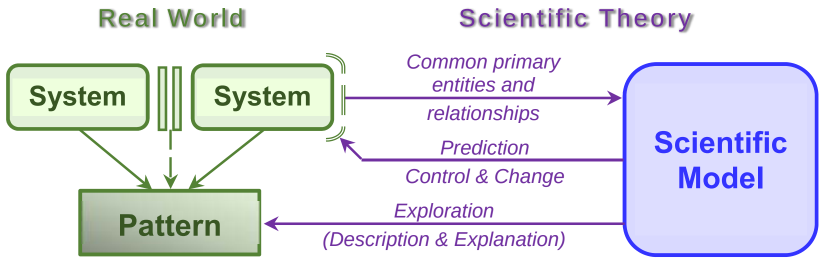

Figure 3. Systemic transaction via a scientific model (conceptual image) with many physical systems manifesting a particular pattern.
Evaluation and regulation take place continuously throughout all processes.

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 in the structure and behavior of physical systems. 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). Science education would better emulate scientists' practice in these respects.

2.2 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 that are repeatedly found throughout 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, 2001, 2004/6, 2017a, 2019b).

Physical patterns are best revealed through systemic transaction 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*). This is especially true in science where patterns of interest are those in the structure and/or behavior of physical systems that may be anywhere and anytime in the universe. Pattern referents, i.e., physical systems manifesting the pattern, would then all be in a similar *state* (or change of state), from morphological and/or phenomenological perspectives, and bring about similar outputs. Science describes and explains this state with a scientific model that represents the corresponding pattern.

As alluded to above (Fig. 3) and discussed next in § 3, a *scientific model* is a *conceptual system*, a humanly conceived abstract system, that corresponds to, or that is mapped onto, only *primary* aspects that are common to all pattern referents. These aspects consist of interacting physical entities and their properties and mutual interactions (or connections or relationships) that are significant to the state of interest (as opposed to *secondary* aspects that are irrelevant to the state in question and that may be ignored). 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 or pattern referents.

Each model is constructed in the framework of an appropriate scientific theory 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. 2) in the framework of the sustaining theory. 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. It is corroborated, and thus inducted in the corresponding scientific theory, if it allows good predictions at the set levels of approximation and 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 (Fig. 3).

3. Model construction

Simply put, a scientific model is a conceptual system that represents, in specific respects and to a certain extent, 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 SCE, physical systems may be defined and conceptual systems constructed using a common template called the *system schema*. The schema may serve scientific as well as pedagogical purposes, and may thus be equally used by scientists on the one hand, and on the other hand, by educationists, educators, especially teachers, curriculum designers and developers of instructional materials, and science students.

3.1 System schema

The system schema is a four-dimensional template that serves for the construction of any system, scientific models included. The four dimensions (Fig. 4), framework, scope, constitution, and performance, are first outlined and subsequently discussed and illustrated in the construction of scientific models.

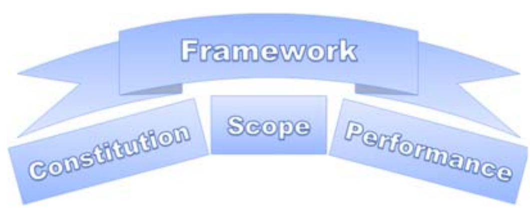

Figure 4. System schema.

1. The *framework* for system delineation or model construction 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 area(s) 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, depending on the nature of the system, 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 of interest;

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 respectively, 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 Framework

Every scientific model (model, for short thereafter) is constructed in the framework of an appropriate *scientific theory* to serve a specific function about the pattern it represents. A scientific theory provides ontological, epistemological, methodological, and axiological principles and rules, along with a necessary epistemic corpus (or content knowledge), for teasing out specific patterns in the universe, and carrying out various modeling processes the most important of which are the construction, corroboration (evaluation and regulation included), and deployment of a particular and exclusive family of models. Models in this family are at the core of the theory's epistemic corpus and have a common set of referents, i.e., physical systems manifesting a particular set of patterns that the theory may deal with uniquely and exclusively. Each model represents one particular pattern, and more specifically one particular state (or change of state) that all referents may be in, and that the model uniquely and exclusively describes and/or explains, among other things (Fig. 3).

For instance, the Newtonian theory of classical mechanics 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. *Particle models* refer to physical objects the internal structure of which may be ignored (shape and dimensions included) when they are in *translation* without rotation or precession, in a specific reference system. All Newtonian particle models may be built and processed for particular purposes following rules implied primarily by Newton's four laws of dynamics. The "first" is the law of inertia, the "second", the dynamical law of cause-and-effect, the "third", the law of mutual interaction, and the “fourth”, the law of force composition. The two most *basic* particle models that are most crucial for students to understand the theory in question meaningfully and develop necessary epistemic and practical knowledge for model construction and deployment are the so-called free particle model and the uniformly accelerated particle model. The first model exclusively describes and explains the rectilinear translation with constant velocity of all physical systems in the absence of external forces (or under a zero net force). The second model exclusively describes and explains rectilinear or parabolic translation with constant acceleration, i.e., with a velocity that varies with constant increments during equal time intervals, of all physical systems under a net constant force (Halloun, 2001, 2004/6, 2007).

3.3 Scope

The *domain* of a model consists of the model *referents*, i.e., of all physical systems manifesting a particular pattern or being in a particular state. The main *function* of the model is the description and/or explanation, in certain respects and to a certain level of approximation, of the pattern it represents, and thus of the common state its referents may be in. 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, e.g., technological artifacts.

Two different models cannot have exactly the same scope. They may have the same domain, whether in the same scientific theory or different theories, but not the same function. Take for example the case of physical objects/systems 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 the same or different physical objects moving at relatively high speeds and/or when high levels of precision are needed.

3.4 Constitution

The *composition* of a 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. 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 and structure of these referents, and not phenomenological aspects like the behavioral state or change of state (e.g., a given type of translational motion in Newtonian theory). The latter aspects 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 one typical interaction law in classical mechanics.

A model is simple or elementary when it consists of a single object concept (e.g., Newtonian particle models), 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 theory of classical mechanics whereby it is often convenient to consider and model physical objects in translation one at a time (elementary 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*, i.e., as constituents of the model environment.

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*. 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.

Newtonian particle models are elementary models with no structure. The composition of each model consists of a single particle with a given mass as the only primary object property to be taken into consideration (shape and dimensions being secondary, and thus ignorable). Unless isolated, the environment of any particle model includes particular agents that exert particular constant or variable forces in an ecology governed primarily by Newton's four laws of dynamics mentioned above. Other generic principles, like Newton's law of universal gravitation, Coulomb's law of electrostatic interaction, and energy principles may also help setting the model constitution.

3.5 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* which a scientific model may be about pertain to the dynamic behavioral 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 (system) 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. Different state laws distinguish different models that may though share the same causal laws (in form but not output).

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 (Fig. 3). 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, laws, and other relationships among concepts that are part of the theory epistemic corpus) are often expressed mathematically 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.

3.6 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 (Fig. 4). 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, and axio-affective.

The four categories, or taxonomy dimensions, are distinguished as such: (a) for practical pedagogical purposes, and, especially, (b) to be in line with the brain structure and functions that can be distributed in four cerebral systems serving and sustaining the four types of learning outcomes (Halloun, 2017, 2019b). Each dimension of the taxonomy, or each type or category of learning outcomes, may be subdivided into a number of *facets* or subcategories some of which specific to a particular field or discipline and others common to many fields or disciplines (Halloun, 2018c).

1. *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.
2. *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.
3. *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.

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.

<table>
<tr><th colspan="2">Schematic dimension / facet</th><th>Sample epistemic aspects</th><th>Sample rational aspects*</th></tr>
<tr><td rowspan="3">Constitution</td><td>Structure</td><td>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.</td><td rowspan="5">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.</td></tr>
<tr><td>Environment</td><td>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.</td></tr>
<tr><td>Ecology</td><td>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).</td></tr>
<tr><td rowspan="2">Performance</td><td>Processes</td><td>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.</td></tr>
<tr><td>Output</td><td>Matter cohesion when interacting and bound with other atoms.
Energy absorption or emission when changing orbits / energy levels.</td></tr>
</table>

* Reasoning skills are distinguished in this column in accordance with SCE taxonomy (Halloun, 2018c).

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.

4. *Axio-affective* learning outcomes pertain to various types of *affects* and *axiological* merits or virtues, especially those that significantly affect student achievement in education. Those affects and virtues include, among others emotions, dispositions, sentiments and attitudes, ethics and values, civics and citizenship. 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, 2018b & c).

The use of the system schema and SCE taxonomy in the construction of scientific models is illustrated elsewhere with ample details in the context of Newtonian theory (Halloun, 2001, 2004/6) and other scientific domains (Halloun, 2018c, 2019a). Table 1 illustrates succinctly how to spell out a scientific model accordingly with the case of Bohr's model of hydrogen like atoms. The table provides sample epistemic and rational aspects (not "learning outcomes" per se) 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 and illustrated elsewhere (Halloun, 2018c).

4. Model organization: epistemic corpus for systemic convergence

Designing a model, or defining a system of any sort and in any field, with the system schema helps putting together the epistemic corpus of any field coherently and in ways that facilitate the systematic and systemic convergence of various disciplines within a given field and among different fields (Fig. 1). Such convergence is further facilitated and optimized when different models or systems are coherently organized in similar ways in different disciplines within the same or different fields. The same is true in education, especially science education. Two major organizational aspects need special attention for systematic and systemic convergence within and with science. The first aspect pertains to the ontological makeup of models and their place in the conceptual hierarchy in scientific theory, the other, to the classification and ordering of various models in a given theory based on well-defined epistemological and cognitive criteria.

Scientific models may be appropriately organized in scientific theory from both inherent, scientific (system schema) and cognitive perspectives. Any given model shares some constitution and performance aspects with other models in the respective theory. However, and as discussed in the previous section (§ 3.3 and 3.5), it is distinguished from other models in terms of its scope (primarily, its function) and some other constitution and performance aspects. Each model is especially distinguished from other models in the conceptual complexity and cognitive demands of the latter two schematic dimensions. Such organizational matters are the object of this section. They must be explicitly accounted for in the design of curricula and related materials, and during instruction so that students can be properly helped to come out of science courses with meaningful and productive understanding of models and theory, and empowered for creative and innovative deployment of these conceptual systems, and for systemic convergence within and among different theories/disciplines.

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 (Halloun, 2001, 2004/6). For instance, the constitution and performance of all particle models in the Newtonian theory of classical mechanics rely on 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 four Newton's laws of dynamics. In contrast, various Newtonian models have distinct state laws (so-called equations of motion) by virtue of which these models are distinguished in their function and performance.

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 and to allow students cross some critical cognitive thresholds and efficiently develop other required models in the same scientific theory.

4.1 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 entities. As indicated in Figure 5, such basic entity is, for us, a system when it comes to the ontology of physical realities, and a scientific model when it comes to the ontology of scientific theory and the epistemology of various sciences (Halloun, 2004/6, 2007, 2011, 2018b, 2019a & b, 2020a).

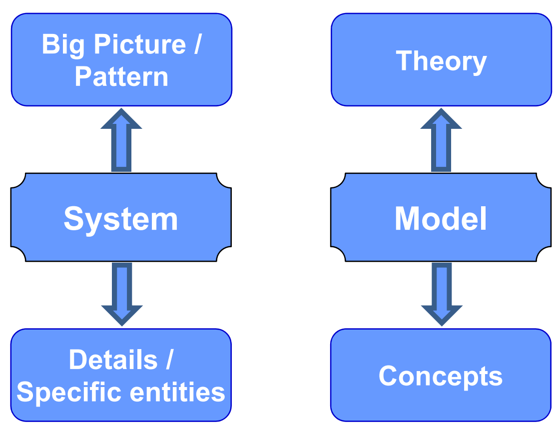

Figure 5. Systems and models in the middle-out hierarchy in the real world of physical realities and the conceptual realm of science respectively.

A 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. 5). 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.

4.2 Critical thresholds

Models in any given scientific theory (and any 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 (§ 3.6) 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.

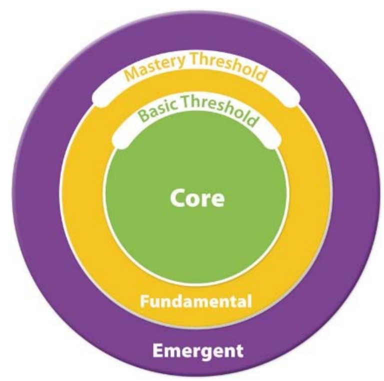

Figure 6. Critical thresholds across models of increasing level of ontological complexity and cognitive demands in a given theory or course.

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, with 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 scientific perspective, and especially (b) a cognitive sequence that should be followed in course coverage from a pedagogical perspective. The most critical of

Box 1. Cognitive demands (Halloun, 2018c).

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.

these thresholds are the "basic threshold" and the "mastery threshold" (Fig. 6). The *basic threshold* separates core models from fundamental models (and related competencies), while the *mastery threshold* separates the latter from emergent models.

In any science course, *core* models are the ones that allow students to develop, in simple forms, basic but critical conceptions, reasoning skills, and dexterities (epistemic, rational, and sensory-motor learning outcomes in our taxonomy), and related specific competencies (§ 3.6) 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 (§ 3.6). *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 (Halloun, 2004/6).

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 circular 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). 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 that students may be familiar with, and that may facilitate the gradual development of the ultimate 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. The first concept is the velocity ($\mathbf{v_o}$) of a particle like object at the instant we begin to explore the translational motion of the object. The second concept is the net constant force ($\mathbf{F}$) exerted on the object throughout its translation.

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 ($\mathbf{v_o}$, **F**) between $\mathbf{v_o}$ and **F**.

The three subsidiary models of Table 2 illustrate, in specific respects, the increasing complexity from core to fundamental and then emergent models (Fig. 6). 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).

5. Model deployment

The model-based transaction of Figure 3 shows major 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 exploratory or innovative purposes. More specifically, direct transaction with physical realities may necessitate the construction and corroboration of new model(s) in the manner discussed in Section 3 above, 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. 3).

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. 4), including the theory itself, and/or (d) the emergence or development of one new scientific 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. Students should be guided to systematically carry out various such regulation and consolidation intentionally and consciously in all sorts of transaction they come across in any 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 terrestrial realities that schools and colleges cannot, and have not to, have access to. Transaction is then simulated or carried out via digital devices or even through textbook examples that may include some photographs of such realities and 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 (§ 3.6 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 proposed next for the main pedagogical purpose of helping students systematize their model-based transaction with the real world (Figs. 2 and 3), and develop some systemic habits for knowledge construction, organization, and deployment. Science teachers of all levels may readily take advantage of the proposed scheme in their courses for many purposes, but especially to help students develop systemic transaction and problem solving habits that they may eventually take advantage of outside the context of a given course, especially for convergence purposes.

5.1 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. 2) 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 4 as well as for the development of the systemic habits in question (Halloun, 1994, 1996, 2001, 2004/6, 2018b).

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 7. 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.

1. *Systemic analysis* is about analyzing the situation at hand in order to: (a) identify the appropriate scientific theory in the context of which all deployment phases need to be carried out, including the 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. 3).

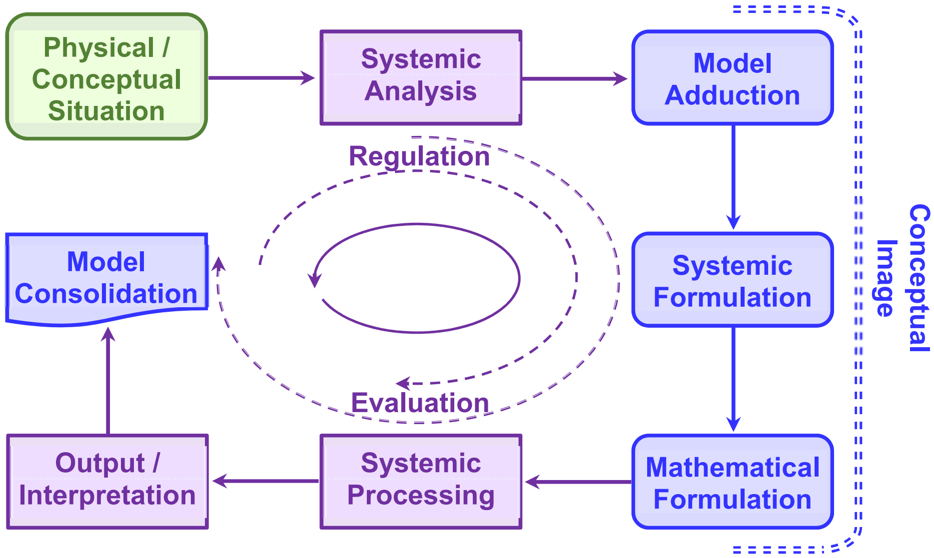

Figure 7. Systemic model deployment, problem solving included.

2. *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 (§ 3.3).
3. *Systemic formulation* is about the choice from the constitution and performance dimensions of each model (§ 3.4 and 3.5) 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.
4. *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).
5. *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.
6. *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 dimension s (Fig. 4).
7. *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 (§ 3.6).

The model deployment scheme is sequential in the sense that no phase can be reached without going through prior phases. However, the scheme is *not* 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 as indicated by the solid curved arrow in Figure 7 and reiterate the process from where it was retaken in order to regulate partly or entirely the work carried out so far.

5.2 Model deployment as model construction in systemic learning cycles

The same scheme of Figure 7 may be adapted to model construction, i.e., to help students construct, in accordance with the system schema of Figure 4 and Table 1, 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 (Table 2) 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 significantly flawed (Halloun, 2018c), 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 get performed.

Model deployment "as" model construction/consolidation 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 7. Each cycle is devoted to the comprehensive construction (deployment included) of a given scientific model in accordance with the system schema of Figure 4. The cycle is experiential in the sense that it continuously involves direct or indirect transaction with physical referents of the model (Halloun, 2018b, 2019b), 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 that may be dedicated to the construction and/or consolidation of particular subsidiary models (Table 2). The cycle is then reiterated as often as necessary, with tasks of increasing complexity, until the target model is appropriately developed and integrated meaningfully and productively in the respective scientific theory.

6. Model-based convergence in science education

Science education lends itself better than other educational fields to convergence, and especially differential convergence, among different branches within a given scientific discipline and from different disciplines, mostly because of the model-based epistemology and modeling methodology that are common to all scientific disciplines. Furthermore, science deals with physical systems and patterns many of which pertain to everyday life and make the object of different disciplines within and outside science all the way to arts and literature. Take the very simple examples of day and night cycle and the change of seasons at any spot on our globe. These patterns have long made the object of, say, physics and geography, to mention a few, as well as many literary and artistic works. The system schema of Figure 4 may serve to analyze and subsequently synthesize together or converge in one modality or another a variety of scientific and non-scientific works pertaining to the two patterns in question (Halloun, 2019a).

Any science course thus readily lends itself to convergence through the construction of models of constituents coming from traditionally distinct disciplines, and of scope and performance spanning a variety of such disciplines in relation to everyday life. This helps bringing coherence and consistency within and among disciplines, and facilitates transfer across disciplines and to everyday life. SCE was conceived to the latter end, especially through purposeful differential convergence in education at all levels, gradually the different modalities distinguished in § 1.3 and ultimately reaching crossdisciplinarity in secondary education and transdisciplinarity in tertiary education (Halloun, 2020b).

Systemic Cognition and Education (SCE) is in itself a pedagogical framework situated at the borderline of crossdisciplinarity and transdisciplinarity. It came about from bridging primarily the following fields: Cognition, educational neuroscience (or Mind, Brain, and Education), philosophy of science, and education. SCE can be traced back to this author's work on modeling theory in science education (Halloun, 2001, 2004/6, 2007, 2011, and related research cited therein and going back to the early eighties of the past century). SCE *emerges* in many respects from the mentioned fields, like in its philosophical and pedagogical tenets and its system schema (Fig. 4). Yet it also *transcends* them in other respects, like in its taxonomy and evolution stages (Halloun, 2004/6, 2017, 2019b, 2020a).

The reader is invited to keep two important points in mind throughout the following discussion of the conditions and advantages of model-based convergence in science education. First, convergence we are calling for is differential convergence among scientific and non-scientific disciplines in the sense discussed above in § 1.3. Second, convergence is meant to take place in the confinements of disciplinary education wherever this is the case. Teachers of different discipline-based courses are called upon to work together on defining issues in their community that can be: (a) tackled only through convergence of their respective disciplines, and (b) feasibly handled by their students. Recommendations on how teachers can handle such convergence projects related to everyday life are provided elsewhere (Halloun, 2020b).

For model-based convergence to be achieved successfully in science education, and subsequently between scientific and non-scientific disciplines, it should explicitly account for all systemic aspects discussed or alluded to above. In particular, it should account for the following aspects:

1. *Systemic frameworks*. Science curricula of all levels should be designed, implemented, and continuously evaluated and regulated under coherent systemic frameworks like SCE. Such frameworks should include common cognitive and pedagogical tenets, principles, and rules that lead to the systematization, across science courses of different nature and level, of identifying, investigating, and taking advantage of systems and patterns in the physical world.
2. *Model-centered, middle-out course design*. The content of any science course should be designed not around individual conceptions (concepts, laws, and other relations among

concepts), but around scientific models with clear correspondence to patterns in the structure and/or behavior of physical systems. Models should then provide the context to develop individual conceptions only when needed for model construction, and not for their own sake, and the vehicle for middle-out conceptualization and coherence of conceptions and scientific theory (Fig. 5). As often as possible, students should be required to deal with convergent models (and physical systems) and guided to do so following explicit rules of correspondence to the real world and to different disciplines. In the process of all the above, students should be explicitly guided to develop necessary rational and sensorimotor skills, and all that is needed to relate models or even conceptions to each other. Developing student competencies to build model-based intra- and inter-disciplinary bridges should be a constant concern in any science course.

3. *Comprehensive system schema*. The system schema of Figure 4 should be thoroughly used in defining any system, and especially in constructing any scientific model. All four dimensions should be attended to explicitly in course work with a special attention to the scope and certain constitution facets of any given model (or physical system). Students often have difficulty identifying the proper model(s) and conceptions for dealing with a given situation, primarily because they are not explicitly taught what a model or conception is good for and under what conditions. Moreover, in the event of a successful model choice, and because they are not taught how to do so explicitly, students often have trouble teasing out primary from secondary constituents and agents in model composition and environment respectively. This leads them to missing some primary entities and properties in model constitution and/or to bringing to the scene secondary and superfluous aspects that do not belong to the model in place.

4. *Systematic model deployment*. Model deployment should be systematically carried out in accordance with explicitly laid out schemes like the one of Figure 7. Students need to be guided to develop their own prescriptive, step-by-step approach to this end, and especially to devise ways and develop the habit to continuously evaluate and regulate their own content and process knowledge. Any given scheme should be extrapolated to cover all modeling processes of Figure 3, especially in a convergence perspective. For all practical purposes, it is advised that construction and deployment of any new scientific model begin with a related subsidiary model in the context of a limited number of physical realities (Table 2), 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(s) of limited scope, constitution, and performance, into the target model with the full fledge schematic dimensions (Fig. 4).

5. *Experiential learning ecology*. All the above can be most efficiently achieved when students are engaged, as often as possible, in direct or simulated transaction with physical realities in line with Figures 2 and 3, with the primary purpose of systematically identifying and modeling patterns in the structure and behavior of well-delineated physical systems, from the subatomic level to the galactic scale. This purpose should be served not only for its own sake and the worthy sake of helping students develop scientific episteme and habits of mind, but more importantly for the prime sake of empowering students with systemic profiles as discussed in the following section.

6. *Assessment as learning*. Assessment under SCE is a systemic endeavor that comes about as an integral part of model construction and deployment. As such, assessment is not an end by itself, and does not culminate with a grade assigned to decide the fate of students. It is rather means to a more worthy end: to systematize systemic learning of course materials and

development of student profiles. Three assessment modalities may be distinguished in education: assessment "of" learning, assessment "for" learning, and assessment "as" learning, with the last modality as most important and 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 *re*produce 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 (Kandel et al., 2013; Markant et al., 2016). Assessment thus becomes an opportunity to develop student knowledge state, i.e., a learning opportunity, whence assessment "as" learning (NASEM, 2017). It especially becomes an opportunity to help students: (a) consolidate what they have already learned about specific model(s) along every facet of the four dimensions of the system schema, and in accordance with all four dimensions of SCE taxonomy (§ 3.6), and (b) extrapolate their content and process knowledge, their competencies, to new contexts in order to expand model scope and output, and eventually all other facets of the system schema.

7. *Personal benefit conviction*. Students axio-affective traits (§ 3.6) should be a conscious and purposeful concern in any science course. Above all, student motivation should be of prime concern to teachers and curriculum developers. Otherwise, and as the plethora of research continues to show for more than half a century now, students will end up learning science loosely and by rote, thus failing to sustain meaningful and productive knowledge in long term memory. The situation can be turned around when students take ownership and control of their learning ecology after they realize the *need* to develop scientific conceptions and skills, especially in a convergence perspective, and recognize in doing so a *personal added value* in two respects, cognitive and practical. In cognitive respects, students should be brought to appreciate the ensuing benefit of continuously answering new questions and solving new problems while bringing coherence and consistency to a wider and wider network of content and process knowledge. Students would be brought to do so convincingly when questions and problems are about practical everyday life situations that matter to their personal and collective welfare and success outside the confinement of school.

8. *Mind and brain alignment*. Mastering various modeling processes and developing crossdisciplinary and transdisciplinary competencies can be brought about only gradually, and as determined by individuals' natural cognitive and physical evolution. The evolution[3] in question is a nature-nurture, brain-mind, product determined primarily by: (a) the biological evolution of people's sensorimotor and cerebral systems, and (b) their experience in carrying out transactions with physical realities along the lines of Figures 2 and 3. Cognitive demands (Box 1) for any model and any experiential learning activity need thus to be carefully identified in the context of the model hierarchy and thresholds of Figure 6 in order to determine what can reasonably be expected of students at any point of instruction. Subsidiary models like those presented in Table 2 can serve to engage students in the gradual development of any desired model.

[3] As per Piagetian theory, there are times, and this is more often the case than not, when students cannot develop certain conceptions, skills, and axio-affective traits unless they have reached a certain level of cerebral growth determined naturally by students' age. In contrast, and as per Vygotskian theory, there are times, and this far less often the case than before, when students can and have to develop certain conceptions and skills in order to induce cerebral development. According to SCE, student systemic profiles evolve in five stages that can readily accommodate the gradual evolution of model-based convergence toward transdisciplinarity (Halloun, 2018c).

7. Model-based convergence for systemic student profiles

Models and modeling in the framework of Systemic Cognition and Education help bring epistemic coherence to students' content knowledge and methodological consistency to their knowledge construction and deployment processes, within science courses and across other courses and everyday life. Such systemic pedagogy thus helps students systematize their learning habits and their transaction with the real world (Fig. 2), 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 already involved (Halloun, 2007, 2011). The pedagogy in question thus readily and feasibly allows for convergence, and especially crossdisciplinarity and transdisciplinarity, among various disciplines within science and between science and other fields.

Model-based convergence brings about many advantages to science education and education at large, and thus to individual student profiles. Some advantages are primarily due to the systemic nature of scientific models, others to convergence, especially as we get closer to cross- and then trans-disciplinarity. Major systemic advantages discussed or alluded to above include:

1. *Ontological-epistemological consistency*. Our transaction with any physical reality involves continuous negotiations between the reality in question and the corresponding conceptual image in our mind in ways that lead to change in knowledge already stored in our memories (Fig. 2). Such negotiations are most effective and meaningful, and the resulting conceptual image most accessible and most productive in subsequent transactions when there is some sort of isomorphism between reality and image (Halloun, 2004/6, 2017, and references therein). This may be achieved when reality and image are both treated as systems, and deliberate mapping between the two is explicitly done at the level of scope, constitution, and performance (mainly relative to primary referent(s) morphological and phenomenological aspects in the latter two respects), under a systemic framework like SCE. Consistency would then be maintained from an ontological perspective between physical realities and corresponding conceptual images (in accordance with the system schema), as well from a related epistemological perspective with and within related knowledge in our memories. Such consistency has the advantage of optimizing the process and outcome of our transactions with the real world, and especially our access to and deployment of necessary knowledge already in memory during the transactions and beyond.
2. *Order in our thoughts and actions*. Such order begins by concentrating on patterns in both the physical world and the conceptual realm of our memories, and revealing patterns systematically in the former world through a systemic worldview. Our long-term memories consist of conceptual patterns sustained in neurological patterns in our brain, and no new knowledge (no new conceptual image) can make its way to long-term memory, and subsequently accessed there, unless it can be readily integrated with existing conceptual patterns by concerned neurological patterns (Halloun, 2017, 2019b, and references therein). Pattern-based conceptual order in our memories and thoughts leading to practical sensorimotor order in our perceptions and physical actions is best ensured through systematic recourse to systemism.
3. *Plasticity and dynamism*. Scientific models are plastic in their constitution and dynamic in their performance, and so are all sorts of systems under SCE. No scientific model is absolute and final. Its constitution is constantly regulated, its performance constantly enhanced, at least in precision and approximations, and its scope constantly refined as a consequence. The same is true about conceptual systems in our memories. Our mind and brain are plastic and dynamic in nature. They continuously evolve, whether or not engaged in experiential

transactions with the physical world, thanks primarily to the inherent dynamism of neural networks that keep working for more and better associations within and between different cerebral areas (*ibid*). Such mental and especially cerebral dynamism and plasticity endows us with potentials for lifelong learning and continuous knowledge evolution, evolution that is optimized when carried out systematically with a systemic worldview.

4. *Holism*. Holism is, for us, about the added value that a system as a whole brings to its constituents and the surrounding environment. A system is *holistic* in the sense that, as a *whole*, it is more than the sum of its parts, and those parts gain their full significance only as system constituents, just like a heap of stones gain significance when used to build a house. The system has *emergent properties* (e.g., the shape of a house) and *synergetic functions* (e.g., dwelling) that no constituent (a stone) possessed individually before. The two holistic features may not be attributed to individual parts and may not be fully understood and appreciated by simply breaking the system into such parts (by analysis or following a reductionist approach). Subsequently, a systemic worldview opens up new horizons for us and takes us to new frontiers that may be neither conceived nor accessible outside such worldview. Take, for instance, the Newtonian theory of mechanics. Newton had it originally conceived and his first disciples deployed in support of the Copernican planetary system. Newtonian models and theory have subsequently evolved to describe and explain the translation of terrestrial objects down to the atomic scale. Euler followed by an extrapolation of the theory in question to describe and explain the rotation of all sorts of physical objects. Both Newtonian and Eulerian theories have then enabled us to "discover" new planetary systems and galaxies in the universe and invent physical artifacts (new technological systems), all of which were not originally thought of in the two theories and their models, but which could not have been possible without such systemic constructs.

5. *Convergence*. A systemic worldview facilitates convergence of various disciplines within and with science, in both academia and the job market, especially convergence between traditionally distinct scientific and vocational and technical fields. SCE was originally conceived to allow for such convergence in education at all levels, and to empower students, especially university graduates, with systemic profiles for smooth induction in modern day society and job market (Halloun, 2017, 2018a, 2019a, 2020a).

Convergence may be brought about in different modalities along appropriate progress or evolution tracks in K-12, with crossdisciplinarity as the ultimate modality in significance and end. In science education, and education in general, convergence can and should be gradually carried out, beginning in the early years with the preservation of the paradigmatic identity and integrity of individual disciplines, and ending in tertiary education with the transcendence of converging disciplines in all respects, i.e., with transdisciplinarity. With such ultimate end of student evolution in mind, many advantages can be realized including the following (*ibid*):

1. *Systematization*. Crossdisciplinarity encompasses and surpasses preceding convergence modalities. When held in K-12 as a common ultimate goal, a common long-term vision, under systemic pedagogical frameworks, it helps maintaining epistemic, cognitive, and pedagogic consistency across various courses and grade levels, and drives teachers and all concerned stakeholders to systematize their instructional tools and practices.

2. *Educational innovation*. When K-12 educational systems and curricula are designed under systemic frameworks like SCE and explicitly work for convergence among different disciplines with crossdisciplinarity as an ultimate end, they can readily provide for coming up with totally novel educational products and practices that transcend traditional divides within and between academic and other professional fields. Traditional divides can then be

transcended between general and vocational education, and primarily between science education on the one hand, and vocational and technical education on the other. Traditional academically focused science curricula, perhaps more than other curricula, are largely disconnected from present daily life and the job market, and can neither attract our students nor empower them for lifelong learning and success in the 21st century. Envisioned systems and curricula would turn things around and allow students and their schools to open up for global trends in our constantly evolving world and convincingly accommodate themselves for constructive engagement in this world.

3. *Aptness for the 21st century*. Crossdisciplinarity and transdisciplinarity work under ultimately new frameworks that are not a mere heterogeneous mix from existing paradigms but that may respectively *emerge* systemically from such paradigms or even *transcend* them altogether. This opens the door for creative and innovative practices and products, including emergent or entirely new disciplines and fields, that could not have been brought about otherwise, at least not as efficiently. Such transcendence is becoming more and more a solid reality in the job market and is thus badly needed in education to ensure sustainable educational systems and curricula that effectively meet the actual needs of individuals' growth and community development in the current century.
4. *Purposeful evaluation and regulation*. With systemic convergence that meets present and prospective realities of the century as a major educational premise, education stakeholders would be convinced to move out of their comfort zones and give up conventional rigid systems and one-size fits all curricula. They would then strive for educational systems and curricula that are plastic and dynamic enough to be continuously evaluated and regulated in order to meet the continuously changing requirements for induction and success in the workplace and every other aspect of modern life.
5. *Systemic student profiles*. All in all, systemic frameworks that work for convergence in education should bring about students with systemic profiles. Such profiles cover in their traits and competencies all four dimensions of the SCE taxonomy (§ 3.6) equitably and in ways to empower students with progressive minds, productive habits, profound knowledge, and principled conduct in all aspects of life, as called for in the 4P profiles of SCE (*ibid*). Profiles in question empower students for self-fulfillment, lifelong learning, and excellence in life, and turn them into well-rounded global citizens who live with and for a strong national identity, and who can contribute to significant sustainable development at the local and national levels.

In conclusion, model-based science education brings about many advantages to all stakeholders, especially to students at all levels. With their systemic nature and reference to patterns, scientific models come ontologically aligned with the structure and workings of the physical universe at all scales and, especially, of human mind and brain, thus providing realistic and efficient means of human transaction with physical realities. From an epistemological perspective, models offer many advantages. First, and among many other advantages, models are optimal means of coherent and efficient knowledge organization within and across disciplines, especially when conceived at the center of middle-out episteme between individual conceptions and scientific theory. Second, and foremost, scientific models come as the optimal vehicles of convergence within all scientific fields and disciplines, and between these and non-scientific fields when the latter, like the former, explicitly adopt in education systemic pedagogical frameworks like SCE to ensure coherence and consistency across all educational fields and grade levels. From a methodological perspective, modeling processes, and particularly model construction and deployment, are common and most important practices in various scientific fields. They help scientists and students alike systematize their transactions with the physical world and their quest for reliable, meaningful, and productive knowledge about this world. With systemic curricular convergence and modeling habits of mind, students, and especially college graduates, are empowered for efficient induction, creativity, and innovation in the workplace where novel, crossdisciplinary and transdisciplinary careers, products, and services are increasingly becoming the norm in present day.

Science teachers and developers of curricula and instructional materials, like students, cannot be left to implement systemic, model-based pedagogy on their own. They need, among others, didactic tools that help them explicitly, and with intensive prescriptive training and continuous support, put together and deploy programs of study and course materials in systematic, coherent, and consistent ways. The SCE system schema, taxonomy of learning outcomes, cognitive evolution thresholds, and model deployment scheme described in this paper are examples of such tools.

Curriculum developers, teachers, and other stakeholders are thus called to adopt systemic (model-based in science) convergence pedagogy like SCE 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. Instructional practices should then focus on fulfilling individual students' needs for systemic learning outcomes and competencies as part of comprehensive student profile development along realistic evolution tracks. The entire educational enterprise would then envision empowering individual students for self-fulfillment, lifelong learning, and success, even excellence, at the personal and collective levels in various aspects of life, and not for merely passing exams of any level or scale.

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