Time to heed resolutely the alarm raised 35 years ago over an everlasting pandemic in science education

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Abstract

In 1985, we published the *Mechanics Diagnostic Test* showing that high school and college students come to their physics courses encumbered with common sense beliefs about the motion of physical objects that are at odds with Newtonian theory, and that students complete these courses without subduing their original beliefs and without sustaining scientific theory meaningfully in their long-term memory. Educational research has since revealed a similar situation all over the world in various science courses at all levels, indicating a universal spread of tenacious common sense paradigms that prevent most students from coming systematically to correct interpretation of physical systems and phenomena. Unlike CoViD-19 and similar epidemics and pandemics that spread for a limited time and that get eventually eradicated through treatment or vaccines, common sense paradigms that are at odds with scientific paradigms have been plaguing science education for ages like a terminal pandemic. Through a recapitulation of our experience with the modeling pedagogical framework, a number of critical factors are identified that turn the situation around and allow for sustainable prevalence of scientific paradigms in student memory.

Keywords

Common sense, convergence, misconceptions, model, paradigm, pedagogical framework, system.

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Thirty-five years ago, we published two complementary articles[1] in the American Journal of Physics about the *Mechanics Diagnostic Test* (MDT) originally developed as part of my PhD dissertation at Arizona State University (ASU) on model-based instruction of Newtonian theory. Four major results came out of administering MDT to high school and college students:

1. Students come to their physics courses with common sense (CS) beliefs about the motion of physical objects that are at odds with Newtonian theory.
2. These beliefs, often labelled as naive, lay, or folk beliefs or conceptions, misconceptions, or alternative conceptions, are deeply rooted in students' minds as part of their overall CS paradigms, and common modes of science instruction do very little to subdue these beliefs and paradigms.
3. CS paradigms govern students' cognitive processes and prevent them from meaningful learning of scientific theory and thus from correct interpretation of real world systems and phenomena.
4. Students may successfully pass course exams by reproducing course materials they learned by rote and retained by heart in their short-term memory. The same students often fail drastically on the same exams given awhile later, indicating that assimilated science materials either did not make their way to student long-term memory (LTM) or, if they did, these materials are being inhibited from activation by CS paradigms that are tenaciously sustained in student LTM.

MDT was revised first into the *Force Concept Inventory*[2], and then to become part of the *Inventories of Basic Conceptions*[3]. Other diagnostic tests and inventories have been developed before and after MDT in physics and other scientific fields all coming, until the present day, to results similar to the ones indicated above in the respective fields. Flawed common sense beliefs have plagued science education for ages like a cognitive pandemic. Unlike epidemics and pandemics like CoViD-19 that health sciences have figured out how to eradicate with proper treatment or vaccines, and will hopefully continue to do so, the cognitive pandemic in science education has so far looked – and wrongly so – as an everlasting terminal pandemic without prospects in sight for eradicating it widely at any educational or geographic level.

Student beliefs about physical systems or phenomena that are at odds with scientific theory can, and must, be understood within the framework of ordinary people common sense (CS) paradigms. According to such naturally predominant paradigms, and among other things, the reality of physical systems and phenomena is exposed directly to our senses, and thus most ordinary people believe that the Sun turns around the Earth because this is the way it appears to us. About four centuries ago, Galileo Galilei, the father of modern science, taught us that this is far from being true and that direct human perception is often deceiving. Thus, in order to understand the universe, we have to transcend our perceptions and imagine how the world could actually exist in a way that is not exposed directly to our senses. As such, we can then realize that the Earth turns around the Sun and not the other way around. In this and many other respects, scientific paradigms are counterintuitive, which makes it hard to let them prevail* over CS paradigms in students' minds without resolute and purposeful efforts in this direction in formal education beginning at an early age.

* Potvin et al.[4] have shown that "acquired scientific knowledge does not necessarily erase or alter initial non-scientific knowledge but rather coexists with it", and "that misconceptions continue to interfere with performance even when there is a higher degree of scientific expertise", which indicates a "conceptual prevalence" of scientific conceptions in experienced people's LTM rather than a "conceptual change" from CS to scientific conceptions.

Traditional science curricula that work primarily on conveying specific aspects of scientific theory – often haphazardly selected – cannot help students achieve such prevalence*, not to mention a Galilean paradigm shift. That is why calls have reverberated, and efforts been deployed within the educational community for decades now to change course, but unfortunately often to no avail. Local noteworthy efforts have been deployed around the globe to this end in two often separate but complementary directions. Most efforts have concentrated on developing student-centered, interactive learning strategies[5] that aim at giving students control over their own learning so that they may supposedly develop appropriate means of knowledge construction and deployment. Other efforts, like in the case of Project 2061 and NGSS[6], have concentrated on identifying generic scientific conceptions and practices that would help students organize their knowledge coherently and deploy such knowledge productively and creatively in a diversity of contexts.

These efforts have engaged a good number of well-accomplished groups and individuals concerned with science education, and costed enormous amounts of money. However, they had so far limited impact and did not pay off significantly at broad local or global levels. Changes brought about in the desired direction by a given group or individual have been hardly sustained, if any, and rarely reproduced at the same level of success by concerned others. Looking at the broad spectrum of high school and college students, researchers keep getting results similar to the ones we published 35 years ago, with no systemic reform producing desired changes at large scale. Our experience suggests that, no matter how gloomy the situation may actually look, there are effective ways to turn things around and bring the so far obstinate cognitive pandemic of CS paradigms under control.

MDT was originally developed not for its own sake, but as part of a battery of instruments designed to ascertain the efficiency of a modeling pedagogical framework that I first conceived at ASU for my PhD dissertation[7], and continued developing afterwards in collaboration with colleagues at ASU and elsewhere. From start, development of the modeling framework went along both directions mentioned above that are part of what I refer to hereafter as academic and cognitive dimensions addressing respectively "what" and "how" to teach and learn things, first in physics and then in science[8]. Our academic perspective is model-laden. As such, we defined scientific models and modeling processes and transformed them from conceptual tools and research methodology for scientists to describe and explain patterns in the structure and/or behavior of physical realities (real world systems and phenomena) to pedagogical means for students to understand such realities meaningfully and answer questions and solve problems about them successfully and creatively. Our cognitive perspective is mind and brain oriented, student-centered and teacher-mediated. As such, we devised the modeling cycle as a comprehensive methodology of guided experiential learning for model construction and deployment and insightful regulation of student common sense conceptions and practices on the long road of the aspired scientific paradigms' prevalence*. Details about the modeling pedagogical framework follow gradually below.

Work with colleagues and student teachers implementing the modeling pedagogical framework throughout the years at the college and pre-college levels (hereafter referred to as "modeling teachers") allowed us to identify a number of factors that are critical for any pedagogical framework, and not only the modeling framework, to succeed making scientific episteme and methodology – and eventually scientific paradigms – prevail in students' long-term memory (LTM). Seven of these factors are outlined in the following. Comparison of the

* Footnote on previous page.

efficiency of various teacher groups mentioned throughout our discussion is made based on their students' performance on inventories[3] like IBC and VASS administered before and after instruction, regular course exams, and large-scale, high-stakes standardized tests.

1. *Attention to both framework dimensions*

A myth, or pedagogical misconception, has long prevailed in the educational community that students are capable, on their own, to: (a) figure out what science, or any other field, is about once exposed to related course materials under the authority of teacher or textbook, and (b) learn these materials meaningfully and sustain them in LTM. Research has always shown that this is far from being the case. Science curricula, and thus pedagogical frameworks in the context of which they are designed and implemented, should be about both "what" to learn about and in science (academic dimension) and "how" to learn scientific episteme and methodology (cognitive dimension). Missing or underestimating either dimension prevent teachers from helping their students develop meaningful and sustainable scientific knowledge that prevails over CS beliefs and paradigms in student LTM. In fact, contrary to their peers who duly cover both academic and cognitive dimensions, modeling teachers cannot bring their students up to the desired level of understanding of science when they concentrate on either model-based content or the modeling cycle but not both.

Any curriculum must explicitly and evenly cover both academic and cognitive dimensions, whatever its academic scope and audience. It must also cover all affective and sensorimotor aspects that affect learning and that are part of comprehensive profile development, especially when a curriculum is designed to empower students for success in life and not merely with specific academic capabilities. To this end, a curriculum must be conceived and implemented under an appropriate pedagogical framework that mandates how to develop individual students' profiles in all respects.

Our discussion is hereby limited to pedagogical frameworks, not curricula, along the academic and cognitive dimensions, and only to the extent that our own experience allows it. Unlike a curriculum that goes into the details of "what" and "how" to teach and learn things, a pedagogical framework specifies only general foundations that help curriculum developers be systematic, and thus coherent and consistent in spelling out needed details within and across different subject matters and educational levels.

The academic dimension in a given framework is primarily about paradigmatic premises, especially epistemological and methodological tenets and principles pertaining to the discipline(s) or field(s) the framework is about. In the epistemological respect, a framework specifies what a given discipline (e.g., physics) or field (e.g., science) is about, how professional (academic) knowledge is generally organized in this discipline or field, and how it relates to the real world. In the methodological respect, the framework specifies how professionals in this discipline or field go about setting and achieving their goals, asking and answering questions, and thus how they go about constructing, corroborating, and deploying their commonly accepted knowledge.

The cognitive dimension is more generic and cuts in many respects across various fields and thus various curricula since it pertains to how people learn in any domain, notwithstanding the fact that every discipline has its own peculiarities that the cognitive dimension needs to pay attention to. This dimension specifies cognitive tenets and principles about how the human mind and brain are and work at different ages, how students can learn meaningfully, and not by rote, what they are ready to learn at specific ages, and how they evolve from a neuro-cognitive perspective across age and school levels. It also specifies rules and guidelines for how learning and instruction should be planned and carried out in formal education settings at every school level. For curriculum developers and especially teachers to carry out their mission successfully, academic and cognitive dimensions need to be spelled out in any pedagogical framework somewhat along the lines discussed next.

2. *Comprehensive attention to each framework dimension*

A pedagogical framework needs to be crafted carefully, and duly corroborated, in both academic and cognitive respects. As mentioned above, the academic dimension needs to reveal in every possible detail what a given discipline (or field) is about, how its episteme is organized, and how professionals in that discipline go about setting and achieving their goals. In these respects, under the modeling pedagogical framework[8, 9], we hold, among others, that:

a) science is primarily about the description and explanation of patterns in the structure and behavior of physical systems;

b) scientific episteme consists of scientific theories, with each theory organized around a limited number of conceptual models representing in specific respects particular real world patterns;

c) scientists construct, corroborate, and deploy conceptual models systemically and systematically to reliably interpret physical realities (describe and explain respective patterns) and deal with them creatively and innovatively (infer their past and predict their future, control and change their states, and invent related artifacts);

d) scientific models and modeling allow for a coherent big picture and efficient knowledge transfer within and among different scientific disciplines, and for efficient and practical convergence between these and non-scientific disciplines;

e) any science curriculum should thus be primarily about scientific models and modeling, and any science course should be organized explicitly around a small set of models that show well enough how the respective scientific theory serves its function at a level that matches students' cognitive potentials.

The cognitive dimension needs to prescribe, based on reliable research in cognitive science and neuroscience, how students may achieve meaningful understanding of the academic perspective above and develop their paradigms and profiles to reasonable levels. To this end, and among other things, under the modeling pedagogical framework[8, 9]:

a) students are engaged, individually and in groups, in experiential learning cycles for model construction and deployment (modeling cycles);

b) students rely on a systemic schema, a generic template for constructing any conception (concepts and relations among concepts) in any field, to construct any scientific model and spell out its details under a specific framework (scientific theory), and in accordance with a well-defined taxonomy of learning outcomes;

c) students deploy a generic, systemic scheme for model construction and deployment, and thus all sorts of problem solving;

d) students are constantly engaged in insightful dialectics for revealing and resolving any issue within their own paradigms, in correspondence to the real world and in commensurability with scientific paradigms;

e) teachers plan efficient modeling cycles, with each cycle dedicated to student construction and deployment of one particular scientific model under teacher mediation involving Socratic dialogues and timely intervention tailored to students' individual needs.

Modeling teachers who cover all five facets mentioned above in each of the academic dimension and cognitive dimension lead their students to better achievement than the students of their peers who miss or play down any facet in a given dimension. Certain facets appear in certain comparative evaluation instances more significant (or detrimental) than others, and other facets do so in other instances. This leads us to the conviction that any pedagogical framework like the modeling framework should be handled as a package deal to lead students to desired ends, with every facet given due attention in accordance with the initial knowledge state of students and their competence at a given point of instruction.

3. *Preserving the integrity of each framework facet*

Teachers are not all expected, and should never be, to handle the same way every facet in every dimension of a given pedagogical framework. A framework should never be designed and adapted as a one-size-fits-all. It should be conceived as, or with the spirit of, a series of flexible standards or benchmarks that individual teachers can adapt, with proper guidelines, to their students' needs in every dimension and facet. However, teachers should never leave out any given dimension or any facet as mentioned above. Most importantly, they should never play down, water down or, worse, misinterpret any facet.

Take for example facet (c) in the academic dimension and facet (d) in the cognitive dimension of the modeling pedagogical framework outlined above (§ 2). With respect to the former facet, some teachers misconstrue a scientific model and water it down to an algebraic equation and/or some other mathematical representation, leaving out all necessary details specified in the four dimensions of the systemic schema mentioned in cognitive facet (b). These dimensions are: (a) the foundational premises of the scientific theory to which a model belongs, (b) the scope of the model (what pattern it represents and what it describes and/or explains about this pattern and model referents, i.e., physical realities manifesting the pattern), (c) its constitution (what entities make up the model and its environment and how these entities interact and affect the model structure), and (d) its performance (how and why the model works, or its referents behave, and what are the outcomes).

As for cognitive facet (d), some teachers water down insightful dialectics to having groups of students exposing their work in class (e.g., on whiteboards) and engaging in discussions about the relative "correctness" of each work. The dialectics in question are however prescribed in the modeling framework along three complementary directions addressing: (a) intrinsic coherence and consistency within one's own paradigm, (b) correspondence to real world systems and phenomena, and (c) commensurability with scientific paradigms.

Teachers who water down these two facets, or any other facet, may help their students reproduce correct answers on specific questions or problems in the short term, but not reach meaningful, generic, and sustainable learning of scientific theory. The situation gets worse when teachers misinterpret the modeling framework, as it has sometimes come to our surprise in the literature, and even much worse when we get misquoted altogether and/or attributed ideas we have always warned against!

4. *Convergence within and with science*

Virtually everything we rely upon in our daily life is the result of convergence among many disciplines or fields, i.e., the result of professionals coming 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 in either profession. The modeling framework, along with *Systemic Cognition and Education (SCE)*[9], the more generic pedagogical framework for student and teacher education that emerged from the modeling framework to serve all fields at all levels, is well suited for educational convergence among various scientific disciplines and between these and non-scientific disciplines[10]. In fact, when modeling teachers engage students in a given course in cross-disciplinary exercises to promote convergence among different scientific disciplines based upon model-based episteme and modeling methodology, students perform better in such a course and are prepared to transfer what they learn there to other courses.

Scientific models and modeling processes readily allow for convergence within all scientific fields and disciplines. As conceptual systems representing real world patterns in the structure and/or behavior of physical systems, scientific models also allow for convergence[10] with non-scientific fields and disciplines, especially when the latter are conceived from a systemic perspective and when related educational curricula are designed and deployed under systemic pedagogical frameworks like SCE.

Convergence we are concerned about is neither about full integration of disciplines nor about any form of supervenience or hegemony that rebukes the merits of any discipline or annihilates it through fusion with other disciplines. Our advocated convergence is *differential*[10] in the sense that it honors and spares the integrity and sovereignty of any discipline in all foundational and practical respects, while recognizing the interdependence of certain disciplines in specific respects and the possibility of any discipline to benefit from other disciplines at any time and place. As such, differential convergence education can take place feasibly and reasonably within traditional discipline-based education[10]. It can, and should, especially help to bridge the traditional divides between general education and technical and vocational education in ways that bring formal education as close as possible to the realities of the job market and the practical needs of everyday life. It should subsequently help students develop at school enough knowledge about the prospects and required qualifications of potential careers so that they would not waste time and money figuring out what major to go for in college / university.

5. *Teaching not to the test but for meaningful learning*

Doing well on inventories like ours, or passing tests and exams of any sort, should never be an end by itself, and teaching to the test, any sort of test, should never be a valued instructional practice. This can never help students learn anything meaningfully, and especially not overcome their CS paradigms. Some teachers using our inventories go over them in class and discuss wrong alternatives on every item, hoping that this would help students overcome their CS beliefs. These teachers become satisfied when their students get subsequently high scores on the inventories, believing that they have actually succeeded to eradicate CS beliefs from students' minds. Similarly, when these or other teachers follow the same practice with typical course exams, and students later perform well on items covered in class, they assume that such good performance indicates meaningful learning of course materials. Unfortunately, this cannot be farthest from the truth. Research has always shown, ours included, that students can memorize by rote correct answers to questions or solutions to problems and succeed reproducing them on assignments and exams without necessarily understanding the science behind those answers and solutions. Moreover, students retain correct answers and solutions in their short-term memory as long as they think they need them for any purpose. Once that purpose served, retained knowledge is unconsciously erased from students' memories and forgotten altogether. That is why the performance of these students drops drastically on our inventories, and other tests and exams, when taken again a few months or even weeks after their apparently good original performance.

The modeling framework is designed to help students not simply answer specific questions and solve specific problems correctly, but most importantly "think like scientists" and develop systemic schemata and schemes that they can deploy systematically to interpret physical realities and answer any question and solve any problem in any context. Modeling cycles are meant to achieve this end by engaging students in model construction and deployment while continuously evaluating and regulating their own thoughts and practices. The three forms of insightful dialectics mentioned above (§ 3) are crucial to help students convincingly realize: (a) the shortcomings of their CS beliefs and practices, including the way they answer questions and solve problems, and subsequently (b) the need to shift paradigm altogether in order to systematically come out with viable answers and solutions to real world questions and problems. Purposeful transcendence of CS paradigms becomes then achievable when students appreciate the value of scientific episteme and methodology in interpreting meaningfully, and dealing creatively with, physical realities, and thus become motivated and gamed enough to develop and sustain such efficient and reliable alternatives.

6. *Reasonable expectations*

Any pedagogical framework and any curriculum should have reasonable expectations about both students and teachers so that both groups may willingly, constructively, and efficiently achieve what is expected of them. Curriculum developers and teachers should be well aware of what students can actually achieve, and how they can feasibly do so, at specific points of instruction, given their natural cognitive state and their educational background. They should especially know how neuro-cognitive maturity determines learning, somewhat in the Piagetian sense, and how learning can determine neuro-cognitive growth, somewhat in the Vygotskian sense. Cognitive science and especially neuroscience are indispensable in this respect.

Among other things, SCE specifies[9] five stages of cognitive development, along with the pedagogical requirements for what students can accomplish at each stage. Systemic tools, including a taxonomy of learning outcomes are also available that help teachers and curriculum developers spell out what students can and should accomplish in each stage about a given scientific model and modeling process (or any system and systemic process outside science).

Meanwhile, curriculum developers, teacher education institutions, and education authorities and administrators should all have reasonable expectations of what teachers can accomplish with their students given, among others, their professional background and the state of the entire ecology in which they are working, including the state of their students, available resources, and workload, incentives, and compensation.

7. *Professional training and support*

Teachers have to be trained and treated as professionals, and they have to carry out their mission as such. Once in-service, teachers cannot, and should not, be left on their own.

Appropriate systems, platforms, and mechanisms should be in place to continuously monitor students and teachers, provide timely support for teachers in need, and ensure efficient sharing of best practices (through some sort of “communities of practice” like professional learning communities) and continuous professional development for all teachers. Moreover, teachers and all other stakeholders must constantly be supported to heed and meet any challenge that may arise, including unprecedented qualifications and needs that could eventually emerge in the job market and various aspects of life and that education must prepare students for.

The modeling pedagogical framework is not a traditional didactic framework for lecture and demonstration about scientific bits and pieces. It is about teacher-mediated student development of meaningful and productive model-based scientific theory and paradigm, including generic means and methods for insightful and regulatory knowledge development, and thus for helping students (and teachers!) transcend their CS paradigms. Teachers need intense clinical training to master and efficiently deploy such a framework, including continuous workshops and support while in service. Our experience suggests that teachers can do significantly better and be more at ease if: (a) the framework is part of their pre-service education at the undergraduate and graduate levels, and (b) curricula they implement are conceived in this framework or another framework that can accommodate, or be adapted to, modeling tenets and principles in both academic and cognitive respects.

Common sense beliefs revealed by MDT and similar inventories are not held by students about specific physical systems and phenomena in isolation of other thoughts and practices. These beliefs stem from overall CS paradigms that govern everything students and other ordinary people think about, and do with, physical realities. Counterpart, scientific paradigms are largely counterintuitive and hard to consider and develop without formal education under appropriate pedagogical frameworks that take into consideration the state of mind of both students and scientists. The modeling pedagogical framework is such a framework, and it has proven viable in over thirty years of practice and continuous development at the college and pre-college levels. With proper training and support, understanding and appreciation of concerned authorities (!), and under appropriate pedagogical frameworks like the modeling framework, teachers can heed resolutely the alarm we raised 35 years ago and tame down students’ CS paradigms to the extent of having scientific paradigms prevail meaningfully in their long-term memory.

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