PIONEER EDUCATION

"What Goes Up Must Come Down"

New, Lower K-12 Science Standards for Massachusetts

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PUBLIC POLICY RESEARCH

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Table of Contents

Background and Executive Summary

New, fully documented, Science and Technology Standards for the teaching and learning of K-12 science in Massachusetts[1] were issued in April, 2016. These were adapted, as the document explains, from K-12 science-education ("STEM"[2]) documents which were named by their authors, and have come generally to be known as, Next Generation Science Standards (NGSS). They were issued in final form by the educational consultancy Achieve, Inc., of Washington, D.C. The official MA standards (MA-NGSS) we now review identify themselves as follows:

> … [These] Massachusetts standards are an adaptation of the Next Generation Science Standards based on the Framework for K–12 Science Education (NRC [National Research Council], 2012). This is done so educators and districts can benefit from commonality across states, including use of NGSS-aligned resources created elsewhere. Common features include:
>
> - Integration of science and engineering practices.
> - Grade-by-grade standards for elementary school that include all STE disciplines.
> - Application of science in engineering contexts.[3]
>
> While the Massachusetts STE standards have much in common with NGSS, public input from across the Commonwealth during the development of the standards identified several needed adaptations for Massachusetts…

One of us (PG) was author or lead reviewer for Thomas B. Fordham Institute studies of successive NGSS drafts, as those were published, first as a Framework from the NRC in 2011,[4] and later as the set of derived, Framework-compliant *standards* from Achieve. Our response to the final NGSS document appeared in January 2013.[5] ZW, too, has studied and evaluated the NRC Framework.[6]

Because the new MA standards are billed as an "adaptation" of the final NGSS standards from Achieve, the Fordham review of the latter, including discipline-by-discipline comment on many representative standards, is relevant to the present discussion. Two short but entirely characteristic statements on the physical sciences (PS) and life sciences (LS) can represent the Fordham review findings on those putative national standards. Note that the quoted statements do not reflect upon the very large body of other, supplementary text in the standards documents. We are here concerned only with explicit standards: *They* alone are to be turned into lesson plans and used to design assessments. (The cited review does respond to standards for all the core disciplines, not just PS and LS.)

The two quotations below represent the tenor of our findings for the new MA-NGSS as well as for their precursor. First, as to PS in the original NGSS, the reviewers wrote:

> …In general, there is nothing in this document that could furnish a basis for the design of a traditional high school physics course or chemistry course. Even for some kind of an introductory ninth-grade physical science course, the material is pretty thin.

And then for LS:

> As in the other core disciplines, there is …. missing content in these Life Science standards. Oddly, on the other hand, several of them illustrate well another, almost contrary difficulty: hyper-compression — that is, cramming into a single standard vast quantities of content [by implication], such that subject matter represented is more like an entire chapter or unit of study in the discipline, than a standard — which is a discrete [teachable and assessable] performance expectation. But these two problems are common to many of the standards.

Our present findings, for the Massachusetts standards, are generally consistent with these observations above, from discipline-specialist reviewers, on the original NGSS. Reviewers' praises (there *were* praises) for the full original documents were and continue to be justified for the admired features; as to the disappointments, however, those remain in force. Unfortunately, for practical and the now immediate purposes of curriculum-making, effective classroom teaching, and assessment design, the praises are far outweighed by the disappointments. Within limited space, therefore, we deal here with just a few of the latter.

The Newest MA-NGSS Standards

Immediate educational issues and the mentioned limitations of space demand reflection upon the standards, as distinct from the laudable social intentions, epistemological certitudes, and currently popular notions on science pedagogy, including especially those first elaborated in the NRC Framework. Most of the latter are present in the MA-NGSS, with abundant, well organized introductory and explanatory front matter. Again, our synoptic comments from the review of NGSS draft II (see endnote 5) — antecedent to MA-NGSS — apply as well to these new MA standards. Here are more samples from the NGSS draft II review:

> In an apparent effort to draft fewer and clearer standards to guide K–12 science curriculum and instruction, the drafters continue to omit quite a lot of essential content. The pages that follow supply many examples. Among the most egregious omissions are: much of chemistry; thermodynamics; electrical circuits; physiology; minerals and rocks; the layered Earth; elements of biological chemistry and molecular genetics; and at least the basic facts and descriptions of embryonic development.[7]
>
> As in [NGSS] version I, some content that is never explicitly stated with regard to earlier grades seems to be taken for granted when referred to [in] later grades — where, we fear, it won't actually be found if the earlier-grade teachers do not see it made explicit.
>
> …[S]cience invariably blends content knowledge with core ideas, "crosscutting concepts," and various practices, activities, or applications. The NGSS mistakenly indicates that presenting science as such an amalgam is a major innovation, in fact a "conceptual shift" — which it isn't. More problematically, the NGSS has imposed, in aid of that shift, so rigid a format on its new standards that the recommended "practices" dominate them, and basic science knowledge — which should be a main goal of science education — becomes secondary. Such a forced approach also causes the language of these standards to become distractingly stereotyped and their interpretation a burden.

The present review agrees on some important points with the evaluation prepared by Prof. S. Metzenberg[8] of a prior MA-NGSS draft. In that account, the author provides an expert unpacking of the tortuous grammar (he called it "verbiage") caused by the single-minded fusion of *Practices* language with content in every standard.[9] We agree with his comments on the frequent superiority of standards in earlier Massachusetts Frameworks for K-12 science.[10] Metzenberg's critique of the earlier version of MS-NGSS is thus generally pertinent to this final version, since many of the problems he identified are still present.

A. Contemporary Scientific Method and Theory Need not Always be Taught From the Very Start

The historical development of science tends to follow common human misconceptions of causation and physical mechanisms. It is a long story littered with *post hoc ergo propter hoc*, at great length and eventually abandoned and replaced by more truth-indicative theory. Following this history, we can retrace and replace our natural misconceptions. This serves us well in discovering reasons for what may at first seem counterintuitive concepts. Examples: a flat versus a round earth, geocentrism versus heliocentrism, and a fixed-earth versus continual change, including continental drift.

The new Massachusetts standards represent the belief that teaching the correct, i.e., the current, modern version from the very beginning is the right approach. Their effort to imprint the current theories, in behalf of "evidence-based" teaching, is visible from the earliest grades in promoting, for example, the modern energy-based particulate model of matter. We are aware of no really persuasive evidence that this is an effective approach to teaching science, particularly when coupled from the very start and consistently with a requirement to *use/provide/analyze evidence*. Rather, it seems to us possible that it could turn into a kind of science catechism.

Young children see the earth as flat, yet they are immediately told earth is a sphere. If we ask them to provide evidence, they cannot themselves truly generate such evidence. All the evidence they can "collect" will surely be provided to them by their teachers, and they will largely take that on faith. Instead of teaching them actually to search for evidence, we will in effect be teaching them to trust the authority that gives them evidence. Moreover, the youngest students do not yet possess the judgment needed to decide whether they are being given the whole body of evidence, or just parts that support a theory under discussion. They will probably *not* ask why, anyway, do they need to provide evidence if they are already told by the same authority that the earth is round. Learning the good arguments, citing the evidence gathered in successful science, is certainly proper, indeed indispensable, for building children's usable scientific knowledge; but that is not quite the same thing as was or is done by the original investigators.

Yet if we were to retrace the evolution of science starting with a flat-earth hypothesis, we would quickly reach the point at which good evidence can be used not only to convince students that Earth is actually round, but also to convince them that a flat-earth theory is flat wrong — and why so. Teaching the evolution of science teaches a healthy skepticism: students see how once-attractive scientific theories can eventually be refuted. Richard Feynman, writing on science teaching, put it in an amusingly extreme form: "Science is the belief in the ignorance of experts."[11]

In other words, it seems to us pedagogically valuable to use evidence not only to prove, but also to disprove, systematically and over time, the more instinctive and simpler misconceptions that have been intrinsic to scientific evolution. Unfortunately, competing "older" theories are essentially invisible in these new standards; history of science is unmentioned in them, and the focus is from very early grades on modern abstract and comprehensive theory and concepts, rather than on earlier, simpler, more accessible ideas to which critical thought and experiment can be applied between K and 12. In science, negative thinking can be, and often is, as important as positive.

The foregoing seems to explain why the new standards insist, for example, from early grades, upon treating temperature and thermal energy in terms of a particulate model, on early introduction of waves and modulation, on attempts to introduce notions of kinetic energy of sound and light. All these and many others are likely to fail when introduced prematurely and will likely just confuse students. The deficiency of this approach is compounded by the fact that there is little mathematical knowledge expected from students before high school, and clarification and boundary statements are used to eliminate any requirement for calculation in service of the concepts. In other words, essentially all of K-8 science in these standards is words about concepts, without requirement or ability to calculate anything. It is apparently easy to forget that mathematical notation is an efficient way to represent thought, even conceptual thought, with clarity and no ambiguity.

B: Overemphasis on, and Confusion about, Modeling

The new standards, Kindergarten and up, are full of language about modeling. They include more than 300 uses of the word "model," such as "use a model," "develop a model," or "build a model." Yet what is intended by this word varies widely and in particular standards is frequently ambiguous.

For example: In Kindergarten, students are expected to "Build a model of a structure that will reduce the warming effect of sunlight on an area," while in grade 2 they are expected to "Develop and use models to compare how plants and animals depend on their surroundings and other living things to meet their needs in the places they live," and then in grade 5 the students are asked to "Use a model to communicate Earth's relationship to the Sun, Moon, and other stars." The desired kindergarten "model" seems to be a physical contrivance possibly offering shade, rather than a "model" of anything. What sort of model, then, can a second grader *develop* "to compare" how plants and animals depend on their surroundings? The desired modeling is even more obscure. Are we referring to pictures and drawings? A terrarium? A computer model? What about the fifth-grade standard requiring "a model to communicate…"? Can a written paragraph serve as a "model" for this case? After all, one can certainly communicate with words!

This mind-numbing exploitation of the word *model* might perhaps have been expected to eliminate the need for, or perhaps make less worrying a dearth of, real mathematical expectations in the standards. Modeling as invoked does seem in places to imply quantitative thinking; but in reality it probably expects little more than drawing a picture. After all, it is unlikely that early elementary and middle-school students — or even many high-school students — will be able to develop genuine miniature, mathematical or computer models, given the mathematically minimalist science they are expected to learn according to the standards. It would be no great surprise, then, if "modeling" were to emerge at its highest level as a feeding of numbers into some opaque but stylish computer program provided by the school, with students having little or no understanding of the scientific principles and processes the program code has been written to simulate.

C. A Few Examples of Flawed and Missing Standards — for Life Science

1. Ponderous and ill-defined standards

A standard:

6. MS-LS1-3. Construct an argument supported by evidence that the body systems interact to carry out essential functions of life.

Clarification Statements:

- Emphasis is on the functions and interactions of the body systems, not specific body parts or organs.
- An argument should convey that different types of cells can join together to form specialized tissues, which in turn may form organs that work together as body systems.
- Body systems to be included are the circulatory, digestive, respiratory, excretory, muscular/skeletal, and nervous systems.
- Essential functions of life include obtaining food and other nutrients (water, oxygen, minerals), releasing energy from food, removing wastes, responding to stimuli, maintaining internal conditions, and growing/developing.
- An example of interacting systems could include the respiratory system taking in oxygen from the environment which the circulatory system delivers to cells for

cellular respiration, or the digestive system taking in nutrients which the circulatory system transports to cells around the body.

State Assessment Boundaries:

- The mechanism of one body system independent of others or the biochemical processes involved in body systems are not expected in state assessment.
- Describing the function or comparing different types of cells, tissues, or organs are (*sic*) not expected in state assessment.

There are problems enough in this standard to require more than its own length for an accounting. Here, however, we are concerned solely with its meaning as an identifier of specific student knowledge or skills — that is, as a performance requirement. First, then, the standard asks for a student-created argument supported by evidence. In fact, such an argument is made (succinctly) by four of the five clarification statements taken together. Included in these summaries are allusions to important facts, and these constitute the key anatomical and functional *evidence* — thus presumed to have been taught or at least offered in the sixth grade or earlier.

It is not at all clear that this latter has been or will be done. Histology and organogenesis are referred to in the second clarification statement, for example, *but then abandoned* in what follows in the assessment boundaries. Even if just the essential facts underlying the physiological *interactions* — which are the focus of this standard — are to be taught in-grade, we are still concerned here with a good part of a term's work in life science, represented in just one "standard." Could that be the intent? But if so, does it not rather call for subdivision into shorter, more specific, and practicable *performances* (standards)?

There is no evidence of adequate prior introduction to the very different types of cells (*e.g.*, muscle — smooth and striated; neurons; leukocytes and erythrocytes, etc.), to their specialized tissues, or to the containing organs. Yet to focus on systems interaction alone, without serious indication of what things in, or produced by, those systems actually interact, reduces the whole standard to a spongy generality. This is in addition to the shortage – even in high-school life science – of appropriate content on the origins and cellular specializations of tissues and organs.

For the moment, however, let us be satisfied that, aside from the blunt contradiction of the standard (*i.e.*, "…supported by evidence…") that is the second assessment boundary, the performance here required is presentation by the student of an informed summary of the basics of all (at least mammalian, if not general animal) physiological system interactions. For a single "standard" that is unreasonable on two grounds.

First, it is overambitious to expect a sixth-grade student actually to "construct" such an "argument." In practice it will usually be a repetition (more or less by rote) of descriptive statements about "systems interaction" presented by a teacher or in readings and showings. Second, any literal assessment of this ostensible student-performance, as described, will have to be based upon the quality of the student's discourse, written or spoken, as much as or more than on knowledge or understanding of the named physiological systems, let alone on knowledge of the actual physiological interactions and regulations — at which this "standard" might seem to be aimed. Some of that may, of course, come later, in high school; or maybe it won't.

Here, for thoughtful comparison, is the better, simpler, more understandable and specific requirement of the essentially corresponding standard for Grades 6-8 in the older (2006) Massachusetts Framework:[12]

6. Identify the general functions of the major systems of the human body (digestion, respiration, reproduction, circulation, excretion, protection from disease, and movement, control, and coordination) and describe ways that these systems interact with each other.

2. Significant omissions: an example

Biological Development

Among the omissions in the life-science standards is biological development, including simple, descriptive accounts of embryology, plus the most basic and accessible (molecular) genetics of cellular differentiation.

One of the triumphs of 20*th*-century biology was the analysis of signaling, genetic, and biochemical mechanisms that cause and control cell differentiation, morphogenesis, histogenesis, and organogenesis in the embryos of multicellular plants and animals. These are the processes that build a functioning adult body from a single cell (in sexual reproduction, from a zygote). The zygote is a cell containing none of the large-scale structures characteristic of particular, functioning body (somatic) cells, and tissues, and organs.

There are passing allusions to or glosses of this material in Achieve's NGSS II (*e.g.*, MS-LS4-d, HS-LSi – e, f, and g), although no precise or systematic coverage. The same is true for MA-NGSS; effectively here any such effort seems minimized. This active field of developmental biology, surely a "disciplinary core concept" within life science, is therefore missing. That, it seems to us, contradicts the firm undertaking of the overview offered in MA-NGSS for HS Biology, to wit:[13]

- From molecules to organisms: structures and processes standards help students formulate an answer to the question, "How do organisms live and grow?"

There is no better generator of interest and excitement among students about questions of "how they live and grow" than to watch, over some little time, the transformation of fertilized chicken eggs, or a batch of fertilized frog eggs, from small, apparently inert specks of material or a mass of tiny spheres in jelly to recognizable, living, and active animals. We note that these questions were essentially also absent from the otherwise clearer Massachusetts 2006 standards.

Modern embryology is no more dispensable than systems ecology. It is perhaps more important for students who will not study biology in college than it is for those who will. The latter will get a thorough introduction to embryology (including human) and some basic biochemical detail of these processes. Other students will get none; and they will therefore not know the answer to what was for long after the discovery of fertilization the great enigma: *Ex ovo omina*, yes; but how does one cell, a mere fertilized egg, know how to turn itself into a functioning adult? What basic biology content is more important than this for the majority of students, who will study no more of it after middle school or early high school?

Cell biology

There follow here some of the problems identified in Metzenberg's 2015 review of these MA standards in draft (and cited, henceforth, as discussed by him). Thus, he wrote for Grades 6, 8, and HS:

In cell biology, it is important for students to learn the parts of the cell and their functions. These draft standards do not include any high school exposure to the nucleus, mitochondria, or chloroplasts. ... No forms of the words 'eukaryotic' or 'prokaryotic' exist at any grade level, nor are important organelles such as 'endoplasmic reticulum' or 'Golgi' mentioned…'[14]

In this final version, we find good, but not major, changes. Important organelles and their functions are indeed now mentioned in the standards (for one example, in 6.MS-LS1-3, and later as well); but skimping on subcellular architecture — as is required by the second assessment boundary— is a significant defect here and in any high-school biology program. Cell biology and a careful selection of details of cell structure and ultrastructure,[15] with associated functions, are essential for initial contact with the most basic modern biology. This is so in its own right, but also in aid of content important for other LS concepts that do appear in K-12 science standards. They include, notably, gene expression in relation to phenotype and in evolution. Mitosis and meiosis are indeed mentioned in the MA-NGSS, and properly so. But then clarification statements and assessment boundaries make it clear that what we consider essential (yet simple) details of these processes and of cytoarchitecture in general — as they emerged in the twentieth century — will *not* be pursued in high school much beyond what was introduced in Grade 6.

For example: Note that the assessment boundary for the otherwise appropriate HS standard HS-LS3-2 undermines what is implied in the standard itself about the need to know and understand some details of meiosis. The boundary contradicts the important item labeled (a) in the standard.

HS-LS3-2. Make and defend a claim based on evidence that genetic variations (alleles) may result from (a) new genetic combinations via the processes of crossing over and random segregation of chromosomes during meiosis, (b) mutations that occur during replication, and/or (c) mutations caused by environmental factors. Recognize that mutations that occur in gametes can be passed to offspring.

Clarification Statement:

- Examples of evidence of genetic variation can include the work of McClintock in crossing over of maize chromosomes and the development of cancer due to DNA replication errors and UV ray exposure.

State Assessment Boundary:

- Specific phases of meiosis or identification of specific types of mutations are (*sic*) not expected in state assessment.

Such attempts as this to avoid the small vocabulary and visualization challenges of important scientific ideas seem to us unnecessary and internally inconsistent. The result is inadequate for "college readiness," at least college readiness among potential STEM-bound students. The justification we have heard (elsewhere) is that for such students these matters can be dealt with in HS "advanced courses" and need not appear as performance requirements of explicit standards, which are supposed to be for everybody. That is not good enough: the basic life science literacy of all high-school graduates needs to include exposure to this material.

Beginning genetics

Metzenberg examined and found wanting the three HS standards that address directly what should be explicitly identified and taught as Mendelian genetics.[16]

He argues that they call for knowledge of Mendel's all-important Laws by indirection rather than by specification, substituting for clarity and specificity such awkward and confusing Practices language and action verbs as "Ask questions to clarify relationships about how DNA in the form of chromosomes is passed from parents to offspring…" (Note, incidentally: Functioning chromosomes do indeed *include* DNA but they have other macromolecular components, whose importance would be evident if some basics of cytology, gene expression, mitosis, and especially meiosis were not explicitly limited, *i.e.*, "not assessed," as in HS-LS3-1and HS-LS3-2 and in other relevant standards.)

The elementary facts and ideas of cell biology and of gene expression need to be included in high-school biology, identified by proper names and terminology. Also, late middle and early high school are the proper and convenient places for Mendel's Laws to be studied *as such*, along with, and at appropriate levels of detail, their physical machinery in the steps of meiosis, fertilization, and development. These can be learned and are in fact being learned at the high-school level easily enough — learned as they have come to be described in the twentieth century.

We note in passing Metzenberg's objections to the specific use in these standards of sickle-cell anemia. It is offered here now as one of several examples of gene/ environment interaction, specifically in the etiology of one human disease. The standard is HS-LS3-4(MA). For reasons Metzenberg gives,[17] there are better elementary examples from which to choose for purposes of that particular standard. It would be better still, however, to offer it separately and clearly as a *locus classicus* of one important genetic phenomenon that often appears, in first learning about dominance and recessivity, to be a flat contradiction: the phenomenon called balanced polymorphism. Simply stated and well taught, it is fascinating and relevant to evolution and the nature of genes. As located and in the standards, however, it is still confusing.

In the present version of the MA-NGSS, some faults in the treatment of basic genetics remain. The obligatory *Practices* language, the asking of questions or "explanations that…" or the making of claims, given first prominence in nearly every standard, serves no special science content-identifying purpose.[18] But it will leave many a lesson-plan designer and classroom teacher deeply uncertain about what to expect the students actually to know and do, and about how to assess what they do. Example: "Make and defend a claim based on evidence that..." The imperative should be something like "State Mendel's Laws with examples of their meanings — for example, in his classical experiments on the inheritance of traits in peas."

Again: The interposition of a *Practices* imperative before every item of content in the standards invites confusion as to (1) which *facts and acts* will count for assessable performance, and at worst (2) making demonstrable knowledge of science secondary to something else (Reading? Writing expository prose? Public speaking?[19]). As we and others have often asked: On what objective scoring system will student performance in response to such standards be assessed?

For contrast, we note that here as frequently elsewhere in the science standards, language and structures for the genetics standards in the prior Massachusetts (2006) Framework dealt with this key content in a direct and immediately understandable way, leaving no doubts for the teacher as to what — respecting Mendelian genetics — can and should be taught, learned, and assessed.

Evolutionary Biology

Regarding another essential topic for K-12 biology, the basic modern-synthesis[20] theory of evolution, at least another of Metzenberg's concerns about genetics is worth quoting:

> …It is important to understand that by failing to adequately address Mendelian genetics in high school, students … cannot learn evolutionary theory in any modern sense. It was Mendel's First Law that actually explicated Darwinian theory, *by* showing how genetic variation could accumulate; how a heritable element could be concealed in a population, in the form of a recessive allele that gives no selective disadvantage, and not be immediately extirpated by the forces of natural selection…

Problems with the HS treatment of evolution mentioned in Metzenberg's review of an earlier draft of MA-NGSS have been addressed. For one small but noteworthy example, Darwin's name *is* now mentioned, as of course it should be, in connection with the theory and the ubiquitous evidence of natural selection. That good fix is only slightly spoiled because of what we trust was a slip in composition:

HS-LS4-2. Construct an explanation based on evidence that Darwin's theory of evolution by natural selection occurs in a population when the following conditions are met: (a) more offspring are produced than can be supported by the environment, (b) there is heritable variation among individuals, and (c) some of these variations lead to differential fitness among individuals as some individuals are better able to compete for limited resources than others.

Clarification Statement:

> - Emphasis is on the overall result of an increase in the proportion of those individuals with advantageous heritable traits that are better able to survive and reproduce in the environment.

Yes, well organized and on the whole well stated – although items a, b, and c *are* in fact the "explanation based on evidence," in concentrated form, first provided by Darwin himself, now sought from the student (and, we trust, supplied by the teacher or recommended reading). But the first seven, unwieldy words are probably one cause of the small but not trivial error that follows, *i.e.*, the need to "construct an explanation based on evidence that "… Darwin's theory of evolution by natural selection occurs in a population…" No. It is natural selection that occurs in a population, not Darwin's theory. Fortunately, this is one of the few errors that can be repaired by a simple edit, and Darwin's name can stay!

For contrast, here is what is essentially all the considerable HS coverage of evolutionary biology in the Massachusetts 2006 Framework. Content-wise, it is as comprehensive; but it is also direct and immediately interpretable as student performance goals. The *kinds* of "evidence" required — *i.e.*, needing to be learned — are plainly specified in item 5.1. There are no unnecessary words.

> 5.1 Explain how evolution is demonstrated by evidence from the fossil record, comparative anatomy, genetics, molecular biology, and examples of natural selection.
>
> 5.2 Describe species as reproductively distinct groups of organisms. Recognize that species are further classified into a hierarchical taxonomic system (kingdom, phylum, class, order, family, genus, species) based on morphological, behavioral, and molecular similarities. Describe the role that geographic isolation can play in speciation.
>
> 5.3 Explain how evolution through natural selection can result in changes in biodiversity through the increase or decrease of genetic diversity within a population.

D. A Few Examples from Physical Science Where the New (2016) Standards Are Less Coherent and More Confusing Than the Old (2006) Standards

1. Water Cycle

The water cycle is, perhaps, the first meaningful example of a reasonably complex *system* to which children can be exposed. Its components – clouds, rain, watershed, bodies of water – are familiar to most children at an early age, and the study of water cycling can tie them all into a real and complete system, illustrating how familiar components interact and make for a complex cycle.

And, indeed, the 2006 MA standards, as in many other states, addressed the water cycle in early grades (3-5). Students were expected to:

> **Describe how water on earth cycles in different forms and in different locations, including underground and in the atmosphere.**
>
> *Draw a diagram of the water cycle. Label evaporation, condensation, and precipitation. Explain what happens during each process.*

Essentially what one would expect: Students learn how the familiar components make the cycle, label them, and illustrate the cycle's dependencies on regional characteristics.

Compare that to the new standards, which in grade 5 expect students "to use a model" (rather than be able to draw and explain). What that model may be is left for the teacher to decide, whether it is to be a computer animation or something even less defined. And no understanding of the driving forces behind the cycle is necessarily expected.

> **5-ESS2-1. Use a model to describe the cycling of water through a watershed through evaporation, precipitation, absorption, surface runoff, and condensation.**
>
> **State Assessment Boundary:**
>
> - Transpiration or explanations of mechanisms that drive the cycle are not expected in state assessment.

The water cycle is revisited in grade 7, this time including the forces behind the cycle:

> **7. MS-ESS2-4. Develop a model to explain how the energy of the Sun and Earth's gravity drive the cycling of water, including changes of state, as it moves through multiple pathways in Earth's hydrosphere.**
>
> **Clarification Statement:**
>
> - Examples of models can be conceptual or physical.

Here students are expected to "develop a model." What hides behind it is anybody's guess, given that the model can be "conceptual or physical." Is a picture enough then? Is a computer program expected? A paragraph of text? An organization chart, with arrows? What physical moving model might students "develop"?

What we have then is an example, in which the new standards fail to leverage knowledge easily accessible to young children, to teach them in plain words about a major ecological system. Not only is such learning unnecessarily delayed, but meanwhile students in grades 3-5 are expected to discuss intelligently sophisticated intangible phenomena, such as differences in organisms' life cycles, developing a model of a wave to communicate wave features, and using a particulate model of matter to explain phase changes. That last is for a fifth-grade student! Really?

2. States of Matter

States of matter is another early accessible topic. Young children tend to be familiar with liquids and solids (water and ice, butter and butter in the frying pan) and gases (steam of boiling water, party balloons).

The 2006 standards take advantage of this and firmly establish the three standard states of matter in the first grade band, **PreK-2**:

> **Identify objects and materials as solid, liquid, or gas. Recognize that solids have a definite shape and that liquids and gases take the shape of their container.**
>
> *Using transparent containers of very different shapes (e.g., cylinder, cone, cube) pour water from one container into another. Observe and discuss the "changing shape" of the water.*

In sharp contrast, the new 2016 standards say (for Kindergartners):

> **K-PS1-1(MA). Investigate and communicate the idea that different kinds of materials can be solid or liquid depending on temperature.**

The grandiose language ("investigate and communicate") cannot hide the fact that children are not expected to know for another five years such basic concepts as what it actually means to be solid or liquid:

> **5-PS1-1. Use a particle model of matter to explain common phenomena involving gases, and phase changes between gas and liquid and between liquid and solid.**

Incidentally, this is the first appearance of the word "gas" in these new standards. One finds it hard to believe that gas is unmentioned until the fifth grade. Don't Massachusetts' children watch water boil or receive balloons on their birthdays?

In any case, the ambitious language here ("Use a particle model") still leaves unclear how a fifth-grader can "explain" phase changes of substances. Is only temperature change expected? Pressure? Which "phenomena" does this standard have in mind? It's all left unclear and for teachers' interpretation. Yet it can't be too deep because in grade eight this standard effectively repeats itself:

> **8.MS-PS1-4. Develop a model that describes and predicts changes in particle motion, relative spatial arrangement, temperature, and state of a pure substance when thermal energy is added or removed.**

It is hard to believe standards-writers expect students in eighth grade to design models predicting "spatial arrangement" or state change based on just change in thermal energy, while the students know very little about classes of substances, beyond such trivialities as "adding thermal energy *may* melt a substance." They should already have known that for a few years before eighth grade.

3. Distinction of weight versus mass

The difference between weight and mass is a fundamental yet difficult concept for students to grasp, and it is critical for understanding physics. The 2006 Framework tackled it in a straightforward manner in middle school (grades 6-8):

> **Differentiate between weight and mass, recognizing that weight is the amount of gravitational pull on an object.**
>
> *Determine the weight of a dense object in air and in water. Explain how the results are related to the different definitions of mass and weight.*

The new 2016 standards never address this fundamental concept. The first real use of "mass" occurs in grade 5, yet the distinction between weight and mass is explicitly *not* made there:

5-PS1-2. Measure and graph the weights (masses) of substances before and after a reaction or phase change …

State Assessment Boundary:

- Distinguishing mass and weight is not expected in state assessment.

From grade 6 and up the use of "weight" disappears and "mass" is used throughout, yet nowhere is the distinction between them ever mentioned.

E. Confusing Standards

1. Inappropriate use of a particulate model.

We have already observed that using the particulate model of matter in early grades is often confusing and cumbersome. Yet a sixth-grade standard that expects students to calculate densities of matter using the particulate model, long before students study atomic and molecular weights, crystal structures, or gas laws, is completely unreasonable and inappropriate.

6. MS-PS1-7(MA). Use a particulate model of matter to explain that density is the amount of matter (mass) in a given volume. Apply proportional reasoning to describe, calculate, and compare relative densities of different materials.

2. Impossible to teach concept.

The photoelectric effect is mentioned in the context of high school physics dealing with the duality of electromagnetic radiation (HS-PS4-3) and in the clarification statement of HS-PS-5 together with solar cell technology. Understanding either of them is impossible without understanding the quantum concept, which is completely absent from these standards.

F. Erroneous Standards

1. Kinetic energy has no exponential relationship to speed.

The clarification statement for grade seven standards is erroneous.

7.MS-PS3-1. Construct and interpret data and graphs to describe the relationships among kinetic energy, mass, and speed of an object.

Clarification Statements:

- Examples could include riding a bicycle at different speeds and rolling different-sized rocks downhill.
- Consider relationships between kinetic energy vs. mass and kinetic energy vs. speed separate from each other; emphasis is on the difference between the linear and exponential relationships.

State Assessment Boundary:

- Calculation or manipulation of the formula for kinetic energy is not expected in state assessment.

The relationship among kinetic energy, mass, and speed is captured by the well-known $E=\frac{1}{2}mv^2$. There is no exponential relationship in this formula, but rather a quadratic one. Further, if using the formula for calculation of energy is not expected for constructing graphs, what exactly is expected by this standard?

2. Gravitational and electrical forces are not proportional to distance of the masses/charges.

The error below was reported by Metzenberg in October 2015[21] for the draft of the standards, yet is left uncorrected in the final version.

7.MS-PS2-3. Analyze data to describe the effect of distance and magnitude of electric charge on the strength of electric forces.

Clarification Statement:

- Includes both attractive and repulsive forces.

State Assessment Boundaries:

- State assessment will be limited to proportional reasoning.
- Calculations using Coulomb's law or interactions of sub-atomic particles are not expected in state assessment.

Specifically, the state assessment boundaries are incorrect in that the effect of distance on the strength of electric force is not proportional, but inverse squared. Further, one might wonder what there is to analyze if calculations using Coulomb's law are not expected. Incidentally, this is one of many examples that illustrate how the new standards avoid using mathematics, even at a basic level, to allow students to gain any sense of the actual forces they are dealing with. The new standards seem to exclude any expectation of mathematical fluency by students and focus almost exclusively on qualitative content, despite their explicit promise to "coordinate[d] with the Commonwealth's ELA and mathematics standards."

3. Confusion between physical and chemical reactions.

Middle school standard PS1-6 says:

6. MS-PS1-6. Plan and conduct an experiment involving exothermic and endothermic chemical reactions to measure and describe the release or absorption of thermal energy.

Clarification Statements:

- Emphasis is on describing transfer of energy to and from the environment.
- Examples of chemical reactions could include dissolving ammonium chloride or calcium chloride.

In general, dissolving salts in water is not considered a chemical reaction but rather a physical process. The new standards erroneously categorize dissolving ammonium chloride and calcium chloride as chemical reactions.

4. Meaningless clarification statement.

High school standard HS-PS1-7 deals with, in a typically convoluted and obscure fashion, balancing chemical equations:

HS-PS1-7. Use mathematical representations and provide experimental evidence to support the claim that atoms, and therefore mass, are conserved during a chemical reaction. Use the mole concept and proportional relationships to evaluate the quantities (masses or moles) of specific reactants needed in order to obtain a specific amount of product.

Clarification Statements:

- Mathematical representations include balanced chemical equations that represent the laws of conservation of mass and constant composition (definite proportions), mass-to-mass stoichiometry, and calculations of percent yield.
- Evaluations may involve mass-to-mass stoichiometry and atom economy comparisons, but only for single-step reactions that do not involve complexes.

The last clause of the clarification statement, "that do not involve complexes" makes absolutely no sense. Complexes of what? Further, the use of the term "atom economy" has no meaning in the context of balancing chemical equations. Sustainability, which is where this concept originates, may be fashionable yet doesn't belong to stoichiometry.

Conclusion

The long and complex document that contains the newest K-12 science standards for Massachusetts is clearly the product of extensive consultation and collaboration among science educators, of hard work and thought about how to implement what is proposed as a new and improved concept of science education.

That concept was first projected in the original NGSS Framework from the National Research Council, and it was repeated, later, in the applied form of actual Standards issued by Achieve, Inc. The resulting Next Generation Science Standards document for Massachusetts is therefore impressive in the same way as its predecessors were impressive: as to the scale and magnitude of effort and ambition it represents.

Yet that does not impel us to issue the "bravo" that so large an effort by so many collaborators might merit. The reasons are simple, and there are just two; but to us they are convincing.

The first is that the pedagogical initiative so central to the design of these documents – beginning every standard with a Science (or Engineering!) Practices imperative or command — weakens the statements of performance. It does so by diffusing and confusing the issues of learning, and knowing-with-confidence, important scientific facts and principles — with matters of discourse, argumentation, and justification. Clarity and simplicity are lost thereby, and we remain unconvinced that there will be learning or other cognitive gains to balance the losses due to weakening or elimination of essential facts and principles expected of students.

The second is a prevalent conviction that scientific literacy and sophistication will be enhanced by consciously (and conspicuously) restricting the range of content in K-12 science, *i.e.*, that depth and sophistication will be emphasized and enabled, rather than mere breadth, as mere breadth was, it is implied, in former curricula. Those predecessors are often described, in this form of argument, as "a mile wide and an inch deep."

That claim seems to us in general invalid; but more to the immediate point, the net reduction of content in these standards, while less than that of NGSS thanks to some Massachusetts additions and repairs, still misses certain specific kinds and levels of content, and important connections, of which we offer here only a few samples. To make matters worse, new, pervasive *additions* of content and arguments — on design, engineering, and technology for example — probably add enough new material needing to be studied and learned, "modeled," or argued, that the implied new curriculum will be no less broad and shallow than were its predecessors. On the face of it, at least for student acquisition of a reasonable if yet elementary science literacy, the new pedagogy seems to us unlikely to be a notable improvement over its recent predecessors — in which the supposedly new pedagogy was largely present anyway in the form of "hands on" and "relevant" and "real world" performance requirements, to be met by the students as a result of "inquiry learning" and by emphasis on "scientific reasoning."

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Endnotes

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2. Science, Technology, Engineering, Mathematics
3. *Loc. Cit.*, 3.
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7. For this last topic, see below.
8. S. Metzenberg. A Critical Review of the Massachusetts Next Generation Science and Technology/Engineering Standards. Pioneer Institute, Boston, October 2015. http://pioneerinstitute.org/education/study-draft-science-technologyengineering-standards-should-be-withdrawn/
9. *Op. Cit.* 7-9.
10. E.g., The Framework issued in 2006. http://www.doe.mass.edu/frameworks/scitech/1006.pdf
11. Richard Feynman. The Physics Teacher, 7(6): 313-320, 1969. http://scitation.aip.org/content/aapt/journal/tpt/7/6/10.1119/1.2351388
12. Massachusetts Science and Technology/ Engineering Framework, 2006. 51. http://www.doe.mass.edu/frameworks/scitech/1006.pdf
13. *Loc. Cit.* 72.
14. They *are* touched upon in corresponding Standards of the current (final) version.
15. For example, the contributions of electron microscopy to what is known about the fine structure and composition of cell membranes, the sarcomere, the mitotic spindle…
16. *Op. Cit.* 2-4.
17. *Op. Cit.* 3-4.
18. Although it might, in the hands of a skillful teacher of reading, speech, and writing (*i.e.*, of *linguistic fluency*), be generally useful. It is by no means special or uniquely central to science or science-and-engineering practices. Linguistic fluency works the same way for History, and for ELA, and it is or should be a key emphasis in the latter!
19. Of course these are all worthy, indeed necessary, acquisitions of K-12 education; but they ought not, *per se*, to have the place of honor in a science standard.
20. "The Modern Synthesis" of evolutionary theory was achieved in the 1940s when the facts and mechanisms of genetics, as they had by that time emerged, along with mathematical and statistical analysis, were applied to the already vast knowledge base of Darwinian natural selection.
21. Metzenberg, *Op. Cit.* 6.

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