Commentary & Feedback on Draft I of the Next Generation Science Standards

June 25, 2012

By Paul R. Gross with Lawrence S. Lerner, John Lynch, Martha Schwartz, Richard Schwartz, and W. Stephen Wilson

Foreword by Chester E. Finn, Jr. and Kathleen Porter-Magee

Contents

Foreword

By Chester E. Finn, Jr. and Kathleen Porter-Magee

In July 2011, the National Research Council released its *Framework for K-12 Science Education*, intended to serve as the basis for a new set of "next generation" standards (NGSS) for primary-secondary school science in the United States. Since then, twenty-six states have come together, managed by Achieve and working with a team of writers, to develop those new science standards.[1] They hope to do for this vital subject what the Council of Chief State School Officers and the National Governors Association did for English language arts and math: develop expectations that are at least as clear and rigorous as the best state standards and that many states may adopt in common, presumably then to be joined by common assessments as well.

The first of two public drafts of those NGSS was released for comment and feedback in May. The authors plan to release a revised second draft in late 2012, with the final standards due sometime in 2013.

It is, of course, premature to comment on the final standards—they don't exist yet—much less to compare them with existing state standards. But a lengthy (and complex) draft is now written (although, unfortunately, no longer accessible online), and it deserves comment.[2] We assume that its authors are sincere in seeking comment, feedback, and constructive advice and that they will take such feedback seriously. In that spirit, we asked a team of veteran science-standards reviewers (plus one veteran math-standards reviewer) to have a look at the draft, and we are pleased at this time to submit the comments and suggestions that emerged from that review.

We at Fordham have a long history of evaluating state, national, and international standards. Indeed, we've reviewed state science standards three times: in 1998, in 2005, and again during the past year. While a few states have done a good job with this subject's standards, most have not. In our most recent review, twenty-six jurisdictions earned D or F grades. Only seven were in the A range.[3]

If students boasted universally strong science achievement, the quality of a state's standards might not matter so much. Unfortunately, as results from the most recent National Assessment of Educational Progress (NAEP) "report card" confirm, American students know very little about science. In fact, barely 2 percent of eighth graders achieved the "advanced" level (and less than one third met NAEP's "proficient" standard).[4] These results provide further evidence that our schools are not preparing nearly enough of our young people to compete on equal footing with their peers across the world.[5]

That is why it is so important that Achieve and its partners get the NGSS right. These standards will function in a number of places as the foundation upon which the rest of the science-education system is built. And getting them right can point curriculum writers, assessment developers, teachers, and administrators in the right direction and set our nation on a path towards improved science achievement.

To that end, the clearest and most rigorous of today's state science standards could provide worthy guides and models for the NGSS drafters. So could the best of today's national and international science standards, such as the frameworks that undergird the Trends in International Mathematics and Science Study (TIMSS) and NAEP assessments in this field.[6] And so, of course, might the NRC's *Framework*.

Particularly because of the intended link between that framework and the NGSS drafting process, we reviewed it, too. Indeed, we asked one of the nation's most respected scientists, biologist Paul R. Gross, to evaluate it with an eye toward how strong a foundation it would provide the NGSS authors. In a report issued by Fordham on October 4, 2011, he found much to praise:

> Like the best of extant K-12 science standards, the NRC Framework's authors have captured nearly all of the content that is critical to a rigorous K-12 science curriculum—real content, too, not what some critics want to dismiss as "science appreciation." The progression of this content through the grades is intelligently cumulative and appropriately rigorous.

He further noted that

> if the statue within this sizable block of marble were more deftly hewn, an A grade would be within reach—and may yet be for the standards writers, so long as their chisels are sharp and their arms strong.

Why strong arms and a sharp chisel? Because Dr. Gross also found within the *NRC Framework* some worrisome tendencies that could easily mislead standards-writers and yield an unsatisfactory product.

Paul Gross also led our team of scientists and science experts who just finished reviewing the first draft of NGSS. And it appears, regrettably, that its drafters (if they paid any attention at all to the Fordham review of the *NRC Framework*) seem to have read only the praise and ignored the potential pitfalls that Dr. Gross had flagged.

They stumbled into three, in particular:

- They went overboard on "scientific practices," seemingly determined to include some version of such practices or processes in every standard, whether sensible (and actionable, teachable, assessable) or not. This led to distorted or unclear expectations for teachers and students and, often, to neglect of crucial scientific content. For instance, students are frequently asked to "construct explanations" or "construct models." In addition to being unclear (how does one "construct explanations"?), such directives imply that *how* students learn the content articulated in the standards is as important as whether they learn it. In reality, content standards should focus on delineating the essential content, and should leave it to curriculum developers and teachers to parse how best to scaffold learning, devise pedagogy, and plan classes.

- At the same time, paradoxically, the drafters left too much to curriculum developers by omitting (or leaving implicit) much crucial science content. In pursuing the objective of *fewer* standards in the (laudable) hope of achieving greater depth of understanding, the drafters sometimes produced only the illusion of content compression. This happens because much substantive content, necessarily linked to a stated standard, is over-summarized in the statement. That leaves said standard, as written, shorn of detail that is in fact indispensable for its use in curriculum planning. Moreover, essential prior content sometimes vanishes. It may be assumed but nowhere is it explicitly stated.

- The alignment between the NGSS draft and the Common Core math standards—something the authors have indicated is a priority—is weak. There are only infrequent and vague references to important mathematics content, which weakens some of the science standards (particularly in physical science in the upper grades) by omitting, for example, valuable lessons that require use of the relatively sophisticated math that the Common Core incorporates. At the same time, however, NGSS sometimes references or expects the use of mathematical content or procedures earlier in the grade sequence than the Common Core provides. That means, for states that adopt both the CCSS math standards and the NGSS, students may be unprepared for the math that their science lessons require—even as, in other places, they may possess mathematical prowess that the science standards fail to exploit for the benefit of more sophisticated and complete scientific knowledge.

In short: Our reviewers judge that the NGSS authors have much to do to ensure that the final draft is a true leap forward in science education. The drafters have ample time to make the necessary changes.

To that end, our reviewers offer four recommendations in the spirit of constructive feedback. These are set forth in Part IV (Recommended Improvements), beginning on page nineteen.

Acknowledgments

We are deeply grateful to the content-area experts who undertook this review: Paul Gross led the team, joined by Lawrence Lerner, John Lynch, Martha Schwartz, Richard Schwartz, and W. Stephen Wilson, all of whom who provided thoughtful analyses of the draft standards on tight deadlines. On the Fordham end, we are grateful to Daniela Fairchild, Joe Portnoy, and Ty Eberhardt for their help preparing the final draft of these standards for public release.

I. Background and Introduction

The writers of the present draft of the Next Generation Science Standards (the first of three, we are advised) honored their charge, namely to prepare a full set of standards—expectations of learning and performance expectations—for K-12 science.[7] These Next Generation Science Standards (NGSS) were to be based on the principles, recommendations, and sample standards in their progenitor—the *Framework for National Science Standards* issued by the National Research Council (NRC) in July 2011 and previously reviewed by the Thomas B. Fordham Institute.[8]

That framework's *science* was sound—hence the B-plus grade that Fordham conferred on it—but it contained several potential challenges for those who would construct actual K-12 standards, curricula, instruction, and assessments atop it. Of particular significance was the NRC's insistence that what it termed "crosscutting concepts" of science be treated as a full partner (a "Dimension") alongside the Dimension of science *content*, which the NRC named "Disciplinary Core Ideas."[9] The same was to be done with another Dimension, "Science and Engineering Practices." And a further challenge was created by the NRC's decision to add to the traditional core disciplines of K-12 science (physical, life, and earth and space sciences) a fourth group of disciplines, titled "Engineering, Technology, and the Applications of Science."

"Crosscutting Concepts"

The NRC didn't invent "crosscutting concepts," which have long been encouraged in science education and are commonplace in existing science standards. They are variously dubbed "themes," "big ideas," and the like. But the *Framework*'s authors broke new ground when they proposed that "crosscutting concepts" be treated in K-12 education as the co-equal of science *content*.

The draft standards are now completed, greatly detailed and in full commitment to the Framework. The resulting product is extremely complex, as is instantly apparent to a reader who undertakes to navigate the full system of documents and web pages comprising this draft. Much thought and website-design knowhow went into the project. Unswerving fealty to the NRC Framework, however, in converting it to a complete set of K-12 standards, turns out to be a source of trouble.

For the most part, that trouble takes two forms: a) an expansionist conception of K-12 science education, combined with b) omission and overgeneralization of scientific content, owing to the drafters' determination to wind up with *fewer* standards than have previously been found in strong sets of standards for this field. In other words, the drafters have sought simultaneously to expand and to compress K-12 science education. That's not necessarily a bad goal, although we have not yet seen it reached. But even in principle, its practical effects on curriculum, on actual instruction, and on the challenges facing assessment—not to mention the nation's long-term scientific prowess—could prove damaging.

In dutifully pursuing the objective of fewer standards (reduction of science-content coverage) in exchange for greater depth, the NGSS drafters sometimes produce only the illusion, not the reality, of content-compression. This happens because much substantive content, necessarily linked to a provided standard, is over-summarized in its statement. That leaves the standard, as written, shorn of detail that is in fact indispensable for its use in curriculum planning and actual classroom instruction. Moreover, essential *prior* content sometimes vanishes. It may well be assumed, but nowhere is it explicitly stated.

Below, we provide some examples of this phenomenon and of the risk—not trivial in this draft—that reducing the number of standards (or science topics) might actually reduce depth rather than increase it. Reduction of numbers or breadth of content standards, that is, of *stated* performance expectations, can have uncertain effects: Once the *implied* subject matter of the written standards is made explicit by the overburdened textbook writer, curriculum director, or classroom instructor, there can be as much content as in a prior, unreduced standards set. But leaving that subject matter implicit handicaps users, who are left somehow to find and fit it in on their own, with no roadmap from the standards themselves.

The present NGSS draft also treats certain generalizations about scientific method and a few pedagogical hypotheses as though they are established principles of science itself. Of course, that has inevitable impact on the form, the extent, and the quality (meaning the rigor and clarity) of the written standards—and eventually on the instruction and assessments based upon them. As explained in what follows, we find some of that impact troubling.

So far as its sample *science content* standards and explanatory comments went, the *NRC Framework* on which these draft standards are fashioned was strong and well argued. In evaluating that framework, substantive content was our dominant concern. However, in turning the *Framework*'s emphases on "practices" (actually, "skills," and typically known elsewhere as "science processes") and on pedagogical hypotheses into actual standards—everywhere integrated, if often clumsily, with substantive content—the NGSS

Organization of the Draft Standards

This draft of NGSS standards was presented in two ways. First, there is a searchable—and very complex, hence relatively difficult to navigate—web module that allows teachers to pull content from various strands and standards and reorder them as they see fit. (Note that this is no longer online.)

Second, the standards are presented in a comprehensive PDF document. There, the standards for K-5 are divided into grade-specific strands, such as "stars and the solar system," or "waves." For each strand, some four to ten standards are presented.

For each strand, the NGSS drafters also included a chart that displays:

1. Components of the *NRC Framework*'s three principal Dimensions ("Science and Engineering Practices," "Disciplinary Core Ideas," and "Crosscutting Concepts") that informed the development of the strand and its resulting standards.
2. The alignment between these NGSS standards and the Common Core state standards for math and ELA.

At the middle and high school levels, standards are organized similarly, *except* that this is done by discipline (life science; physical science; earth and space science; and engineering, technology, and applied science) rather than by grade. There are thus two large grade bands, one for middle school (presumably grades 6-8), and the other for high school (grades 9-12.)

writers have caused those emphases to become (in our opinion) an impediment, rather than a contributor, to curriculum-building.

A steadfast focus upon conceptual understanding—as opposed to traditional conceptions of scientific knowledge, including key facts and formulas—is the driving educational goal of the *Framework* and of this NGSS draft. But no clear, workable definition is offered that distinguishes "conceptual understanding" from knowledge of a science topic. In the absence of a workable distinction, there is no guidance toward efficient measurement of many learning outcomes, mostly those that are intended to consist of "understanding" rather than "knowledge."

In Part II, we comment upon some of the standards written for the three now-traditional core disciplines of natural science (physical, life, and earth and space sciences), with which scientists and science educators are quite familiar.[10] In Part III, we consider the alignment of such mathematics as is to be found in this NGSS draft with the Common Core math standards (CCSS-M). And in Part IV we offer some suggestions to those who will be revising the present draft.

II. Content Strengths and Weaknesses in the Core Disciplines of Science

These standards display merit, sometimes in a single, well-written standard, sometimes in the approach to and coverage of a broad content topic. Evolution standards, for one example, are straightforward, accurate, and grade-appropriate. We could cite other examples. But our purpose in this section is to flag characteristic problems that we encounter in the present NGSS draft. Hence the example standards and reviewers' comments shown in this section are illustrations—in fact, a small sample of our observations. We selected them as representative of generic problems. At this stage, providing further examples would not alter the purpose of our review, which is to identify what seem to us the significant needs for improvement, and to suggest some means by which these might be addressed in subsequent versions.

Although our discussions (for the most part) start with Kindergarten standards and end with those of high school, we do not move up through the grades with stops at each grade or band. The samples shown were chosen because each one represents some or many other standards that give us the same disquiet. Problems that these sample comments represent are, in fact, common in the treatment of all the core disciplines.

NB: "Clarification Statements" accompanying the standards reproduced below are from the NGSS draft, i.e., they are the authors' clarifications, not ours.

Physical Science

There are several critical problems with the physical science standards. To begin, many topics are introduced at one grade level and then never seen again at higher levels. In addition, phraseology is often clumsy or worse, misleading. Take, for example, the following high school standard:

> Plan and carry out investigations in which a force field is mapped to provide evidence that forces can transmit energy across a distance. (high school; forces and energy)

This is backward. The fundamental fact is that some forces act at a distance. The properties of such forces are well described by the field concept. It makes no sense to say that the field provides energy for the forces. Moreover, it is inaccurate and confusing to assert that forces transmit energy. More correctly, a force field can be mapped in terms of potentials, which can be used to infer the potential energy possessed by an appropriate particle (e.g., a charged particle in an electric field) located at any particular point. Further, the phrase "plan and carry out investigations" contributes nothing useful—other than to flag the pedagogical hypothesis driving the drafters' commitment to create a nexus of "practices" with what used to be recognized as *content*.

Next problem: Some seemingly attractive ideas are offered that, unfortunately, can't work. Consider, for instance, the recommended treatment of "structure and properties of matter" at the Kindergarten level (K-SPM). Broadly, what is presented under this heading is appropriate for Kindergartners and could be useful for stimulating their curiosity. But it is spoiled, for example, by the following standard:

> Plan and carry out investigations to test the idea that warming some materials causes them to change from solid to liquid and cooling causes them to change from liquid to solid.
>
>> [Clarification Statement: Students could investigate substances like butter, chocolate, ice, cheese, or ice cream. Students should be able to have the opportunity to see that not all substances' phase changes with temperature.] (Kindergarten; structure and properties of matter)

The "clarification statement" is itself opaque, since all substances do experience phase change at *some* temperature—but which may be outside the range observable by Kindergartners. Far more troubling here is the poor choice of examples. Of the five given, four (butter, chocolate, cheese, and ice cream) do not experience classical, simple phase changes on melting. This is a very common fault seen in many standards. (One wonders if the writers have ever tried to reconstitute butter or ice cream by cooling the melt.)

In a related standard in grade two (2-SPM), we see a compounding of the same problem:

> Provide evidence that some changes caused by heating or cooling can be reversed and some cannot.
>
> > [Clarification Statement: Examples of reversible changes could be melting chocolate or freezing liquids. Irreversible changes could be cooking food.] (grade 2; structure and properties of matter)

Chocolate is an emulsion, and if one melts and re-solidifies it, one will end up with a product quite different from the starting material (and a lot less attractive). To say the least, the process is *not* "reversible."

Further confusing these standards is the clumsy request that students "provide evidence that…." We discuss this problem in greater detail in Part IV, but the drafters' commitment to specific identification, everywhere in the standards, of at least one scientific practice (usually a cognitive habit or a skill present in all recognized science content, and therefore not requiring endless repetition) causes the language of many of the standards to become needlessly stilted, and—more important—puzzling and distracting for curriculum writers and especially for teachers.

Here is another example of the problem posed by slavish dedication to the incorporation of scientific practice into every standard:

> *Communicate arguments to support claims* that Newton's laws of motion apply to macroscopic objects but not to objects at the subatomic scales or speeds close to the speed of light. [emphasis added] (high school; forces and motion)

This gives no hint as to what is truly expected of the student. Aside from the illogical internal structure of the sentence, the inapplicability of Newton's laws at small scales and/or high speeds is not at all a matter of "claims," but a *fundamental property of nature*. And just which "arguments" is a student expected to "communicate," and by what means? Is she to describe the implications of the Michelson-Morley experiment, or the Lorentz invariance of Maxwell's equations? If not, what then? This is a plea, not for depth but for superficiality.

At the high school level, the quantitative approach to physical science is severely short-changed, and a number of important subjects are missing entirely. Among these are kinetic theory, heat and thermodynamics, physical and geometric optics, as well as any treatment of modern physics *beyond* a bit on nuclear processes. It appears that the quest for fewer standards has led to the omission of a great deal of "prior content" that is actually essential. Take, for example, the following:

> Use arguments to support the claim that electromagnetic radiation can be described using both a wave model and a particle model, and determine which model provides a better explanation of phenomena. (high school; electromagnetic radiation)

This asks quite a lot of the innocent student who has no background in Maxwell's equations, wave-particle duality, or a bunch of other indispensable prior concepts, the assessment of which would be a nightmare unless "pass/fail" is good enough. One wonders whether the drafters have replaced true college- and career-preparedness in the field of science with some notion of "scientific literacy."

Missing at all levels are: electric circuits, any discussion of such basic quantities as voltage, current, and resistance (let alone alternating-current quantities), Kepler's laws, and rotational mechanics.

Among the Disciplinary Core Ideas within the high school electromagnetic radiation standards, we have: "Electromagnetic radiation (e.g., radio, microwaves, light) can be modeled as a wave of changing electric and magnetic fields or as particles called photons. The wave model is useful for explaining many features of electromagnetic radiation, and the particle model explains other features. Quantum theory relates the two models" (PS4.B). This is a good and very big handful, and it comes directly from the *NRC Framework*. This is not to fault the framework—but it presupposes that resulting standards to accompany such large core ideas would be written with sufficient content specified to provide the minimum background needed for understanding, e.g., the models and the reconciliation (in quantum mechanics).

Among the resulting standards, a scaffolding should exist to identify the necessary steps toward respectable modeling. There really ought to be at least some mention of the fact that Ampère's law and Faraday's law, taken together, can give rise to an electromagnetic wave in free space. But there is nothing like that to be found in this draft. Instead, we find this:

> Use arguments to support the claim that electromagnetic radiation can be described using both a wave model and a particle model, and determine which model provides a better explanation of phenomena. (high school; electromagnetic radiation)

What "arguments" is the typical high school student expected to present that will make any sense to her? Standards like this (of which there are numbers) produce the antithesis of the intellectual depth which reducing the number of standards is supposed to permit. Again, the drafters may be seeking "literacy" about science rather than true readiness for college-level science. As rewritten in this first draft of the NGSS, they beg for simplified, qualitative, easily remembered responses.

In the nuclear processes standards at the high school level, we see: "Spontaneous radioactive decays follow a characteristic exponential decay law" found among the Disciplinary Core Ideas. This is both true and significant, but no mention is made *in the standards themselves* of the fundamental fact that this (decreasing) exponential decay law is a direct consequence of the randomness of the decay of individual nuclei in the sample being observed. Here again, the standards as written do not introduce or sequence recognizably the content needed to understand a broad "Disciplinary Core Idea."

In the same section, we have: “Construct models to explain changes in nuclear energies during the processes of fission, fusion, and radioactive decay and the nuclear interactions that determine nuclear stability” (high school, nuclear processes).

Fission, fusion, radioactive decay, and the nuclear interactions that determine nuclear stability are each *major* topics! Cramming them all into a single standard is a bad idea, especially if “models” are really to be “constructed.” Either it demotes the content to loose, qualitative assertions, or it turns the single standard into an omnibus—in this case a full unit of high school physics.

Finally, there is a small but nontrivial number of flat errors in scientific statements. Here is an example:

> Investigate physical properties of materials and use the properties to distinguish one material from another.
>
> > [Clarification Statement: Examples of physical properties can include salt dissolving in water while sand does not; copper wire conducting electric current and shoelaces do not; a metal spoon conducting heat and a wooden spoon does not.] (grade 5; structure and properties of matter)

It is wrong to say that wood does not conduct heat. It does, just not as well as metal! This standard is also an example of missed opportunities to introduce appropriate vocabulary: here, for example, *insulator*.

Chemistry (within Physical Science)

The NGSS drafters sought to address fewer topics but at greater depth and to build a thorough content base from grade to grade. But this draft achieves only the first part of the first goal—fewer topics. It accomplishes this by radical reduction of the content found in a typical high school chemistry class. The drafters also avoid using appropriate grade-level vocabulary and almost completely omit mathematical problem solving. When the document was searched for the word “calculate,” not a single reference was found. We find nothing resembling a sufficient basis for a high school chemistry course, nor any discussion of organic chemistry or biochemistry. A word search was conducted to verify what seemed to be a lack of chemistry content. The following key chemistry terms and concepts are *absent* from the document:

> Chemical equilibrium; Le Châtelier’s Principle; covalent; metallic; hydrogen bonds; bond angles; molecular shapes; ions; electrolysis; precipitate; stoichiometry; and molecular formulas; bases and the pH scale; balancing chemical equations; the mole concept; gas laws; and electron configuration.

There is a reference for “acid rain” in earth science and “nucleic acid” in life science, but nothing on “acids” in physical science where one must expect this essential aspect of chemistry to be taught and learned.

Life Science

Let us begin this time in Kindergarten, first looking at the NGSS standards for "organisms and their environments":

> Use observations to describe how plants and animals depend on the air, land, and water where they live to meet their needs, and they in turn can change their environment.
>
> > [Clarification Statement: Examples of how plants and animals change their environment could include ants making anthills, plant roots breaking concrete, or beavers building dams.] (Kindergarten; organisms and their environments)

Of course plants and animals change their environment! But the chosen emphasis is misleading so early in the child's schooling. It implies changes imposed by individual actors on a constant, passive, unchanging substrate: "the environment." That's not how the world is. Plants and animals *are* the environment, or key parts of it. They and it are always changing, and mutually changing one another. This reality (which is actually noted in later grades) can be conveyed appropriately here by changing the language of the standard. And of course "Use observations to describe" is formulaic: It merely brings the "practices" Dimension into a *nexus*-standard once again, though it's hard to picture what exactly is expected in this regard from five-year olds. The next standard is then:

> Use observations and information to identify patterns in how animals get their food.
>
> > [Clarification Statement: Animals get their food by various means. Some animals eat plants, some eat other animals, and some eat both.] (Kindergarten; organisms and their environments)

Language is again the trouble here, not the (entirely appropriate) knowledge to be acquired. That some animals eat plants, etc., is *just a fact*, not a "pattern." Carnivory, herbivory, omnivory are not patterns. "Using" observations and information amounts at this stage (Kindergarten) to no more than hearing from the teacher, or seeing in a book or a display, the given facts—or perhaps, under teacher guidance, watching an animal (or oneself) eat a plant. The elevated "practices" language does nothing useful. Moreover, "identify patterns" implies cognitive competences that just aren't there and won't really be acquired by children this age. Yet such a standard could leave a conscientious Kindergarten teacher in a quandary about implementation and assessment. Finally in this section, we have:

> Provide evidence that humans' uses of natural resources can affect the world around them, and share solutions that reduce human impact.
>
> > [Clarification Statement: Examples of how humans' uses of natural resources can affect the world include cutting trees for lumber and paper products or discarding plastic bags and other waste that affects animal habitats. Humans can reduce their impact by recycling and avoiding littering.] (Kindergarten; organisms and their environments)

So early in schooling, ideology and politics already rear their heads! They are neither necessary nor useful at this point. On the other hand, a standard emphasizing the first clause of this standard would be sound, valuable, and far more practical for the purpose.

Similar issues arise in the "structure and function" vein of standards—throughout the grades:

> Ask questions to define a problem and design an object that replicates the function (use) of a structure (part) present in an animal or a plant to address the problem.
>
> > [Clarification Statement: Examples of a device could be a device to pick up small objects based on an animal structure such as a bird beak.] (grade 1; structure and function)

"Design an object that…" This is a forced effort to incorporate "practices" and engineering, as the emphasis is on "design." The effort might help a few very able or imaginative students to see that some biological structures work like simple machines, or, less likely, how inventors might think. But few first graders are ready to take on board abstractions about human design versus evolved adaptations of biological structure. Just as important: What is actually expected of students in a standard that says they should "ask questions to define a problem"? How does this help the curriculum designer or classroom teacher, much less the test developer? And at the middle school level:

> Construct an explanation for the function of specific parts of cells including: nucleus, chloroplasts, and mitochondria and the structure of the cell membrane and cell wall for maintaining a stable internal environment. (middle school; structure, function, and information processing)

The omnibus (or over-concentration, under-specification) problem is here seen once again. Where will a middle school student find the necessary basic information on the *functions* of each organelle? She will certainly not "construct" or "discover" them! And how will she know and show that a combination of those functions identified will produce "a stable internal environment"? The latter needs at very least scrupulous prior definition, which comes, usually, only with considerable knowledge of cellular and organismal physiology—unlikely to happen in middle school.

The situation does not improve much in high school, where we find many more omnibus standards, each of which implies a large body of important content, but does not specify what exactly is to be learned, i.e., does not provide explicit "performance expectations." For example:

> Obtain and communicate information explaining how the structure and function of systems of specialized cells within organisms help them perform the essential functions of life.
>
> > [Assessment Boundary: Limited to conceptual understanding of *chemical reactions that take place between different types of molecules such as water, carbohydrates, lipids, and nucleic acids*.] [emphasis added] (high school; structure, function, and information processing)

How are students to do this without prior preparation in the relevant elementary organic and metabolic chemistry, of which there is no evidence in the draft? To what (specific) "reactions" do they refer? Of reactions in general there are multitudes among those molecular species.

> Communicate information about how DNA sequences determine the structure and function of proteins.
>
>> [Assessment Boundary: Limited to conceptual understanding of how the sequence of nitrogen bases in DNA determine the amino acid sequence and the structure and function of the protein it codes for, not the actual protein structure.] (high school; structure, function, and information processing)

This is an important topic and highly appropriate for high school. But what does "communicate information" mean here, specifically, within the strong limitation of that Assessment Boundary? Parrot what has been said by the teacher, or what is shown on a cartoon of the nominal steps in protein synthesis? And how will they do this without knowing at least some elementary chemical description of those "nitrogen"(ous!) bases? Finally, how can a student speak of the structure and function of proteins if nothing is to be said about "actual protein structure?" It is possible to divine here the writer's meaning, but many teachers will not be able and should not be expected to do so. Moving on:

> Evaluate data to explain resource availability and other environmental factors that affect carrying capacity of ecosystems.
>
>> [Clarification Statement: The explanation could be based on computational or mathematical models. Environmental factors should include availability of living and nonliving resources and from challenges (e.g., predation, competition, disease).] (high school; interdependent relationships in ecosystems)

Which "computational or mathematical" models? How? This omnibus standard implies an important unit in an elective course or textbook on systems ecology. As expressed in this standard, the basic (and grade-appropriate and important) issue—i.e., carrying capacity—is too general and much too vague for such use. "Computational or mathematical models" leaves everything to the student (or teacher). The statement conveys zero mathematical content. And then in the "inheritance and variation of traits" domain, there's:

> Use a model to explain how mitotic cell division results in daughter cells with identical patterns of genetic materials essential for growth and repair of multicellular organisms.
>
>> [Assessment Boundary: The focus is on conceptual understanding of the process; the details of the individual steps are beyond the intent.] (high school; inheritance and variation of traits)

Why beyond the intent? Those details (e.g., stages of mitosis, stable chromosome identity—"patterns of genetic materials") are simple enough, and are both essential and informative for what follows in subsequent, related standards. *Knowing* the details of mitosis is a critical first step in *understanding* the contemporary picture of inheritance. The Assessment Boundary looks like a way of shielding students from the need to learn a few elementary hard facts of biology. But this is high school! Finally we have:

> Construct an explanation for how cell differentiation is the result of activation or inactivation of specific genes as well as small differences in the immediate environment of the cells.
>
> > [Assessment Boundary: Limited to the concept that a single cell develops into a variety of differentiated cells and thus a complex organism.] (high school; inheritance and variation of traits)

This standard takes up a fundamental issue, one that is important for life science at the high school level. But there is no evidence that the necessary background in developmental genetics has been or will be available. As drafted, the standard presents an impossibly tall order, based on what has been indicated (and omitted) heretofore: for the student (or teacher!) simply to "construct" such an explanation, including the *evidence* for differential gene activity and signaling processes in morphogenesis. Specified in a series of simple, *explicit* standards that include the requisite prior knowledge, it could serve as the performance expectations for an entire unit of high school biology.

Earth and Space Science

Much explanatory science content is missing that is needed to support the apparently ambitious goals of this effort. Glaring omissions include earthquakes and volcanoes as phenomena, as well as details about kinds of minerals and rocks—things that children usually enjoy learning about. In the higher grades, we encounter again the problem of omnibus standards.

In third grade:

> Analyze and interpret weather data to identify day-to-day variations as well as long-term patterns.
>
> > [Clarification Statement: Examples of weather data could include maps and forecasts. Students should address climate in terms of long term patterns.] (grade 3; weather, climate, and impacts)

A weather map primarily features isobars—lines connecting points of equal air *pressure*. Yet the concept of pressure is not taught explicitly: The term itself does not show up until high school. So weather maps are premature here unless much more advanced science (unmentioned in the present draft) is actually supplied. "Forecasts" per se can hardly reveal "long-term patterns" to third graders. In the middle school "earth's surface processes" standards:

> Plan and conduct investigations to explain how temperature and salinity cause changes in density which affect the separation and movement of water masses within the ocean.
>
> > [Assessment Boundary: Complex system interactions such as the Coriolis Effect are not required.] (middle school; earth's surface processes)

Density is not developed as a concept prior to this important but complicated idea. It is later discussed as a property. Within the same section we have:

> Plan and carry out investigations of the variables that affect how water causes the erosion, transportation, and deposition of surface and subsurface materials as evidence of how matter cycles through Earth's systems. (middle school; earth's surface processes)

What are these "materials?" Have students previously learned anything about the minerals and rocks, how they are made, and have they learned about how they weather? Or is it just water picking up material and depositing it? And what sort of "investigations" are meant or imagined here? Then there's:

> Construct explanations for patterns in geologic evidence to determine the relative ages of a sequence of events that have occurred in Earth's past.
>
> > [Clarification Statement: Evidence can be field evidence or representations (e.g., model of geologic cross-sections). Events may include sedimentary layering, fossilization, folding, faulting, igneous intrusion, and/or erosion.] (middle school; the history of Earth)

This is an enormous amount of geology to cram into *one* "performance expectation," much of it not yet supported by background learning. This is the first occurrence, for example, of the terms "igneous" and "faulting." Nor is it clear what—besides fealty to constructivist pedagogical theory—is served by asking middle schoolers to "construct explanations for patterns" that the standards do not show ever having been taught. Also at the middle school level:

> Plan and carry out investigations that demonstrate the chemical and physical processes that form rocks and cycle Earth materials.
>
> > [Assessment Boundary: Students should use various materials to replicate, simulate, and demonstrate the processes of crystallization, heating and cooling, weathering, deformation, and sedimentation involved.] (middle school; earth's interior processes)

The rock cycle, finally. But it is hard to claim that there are now fewer standards when just one like this spans what could easily be the better part of a semester's geology course! This is another example of negative consequences of the quest for fewer standards (and the imagined depth to follow). And then we have:

> Use mathematics to analyze weather data and forecasts to identify patterns and variations that cause weather forecasts to be issued in terms of probabilities.
>
> > [Clarification Statement: Averages and basic probability should be used to analyze weather data.] (middle school; weather and climate systems)

The clarification statement doesn't begin to help a reader understand *just what mathematical work is envisioned*. The high school level standards offer still more examples, like:

> Construct an evidence-based claim about how a change to one part of an Earth system creates feedbacks that causes changes in other systems (e.g., coastal dynamics, watersheds and reservoirs, stream flow and erosion rates, changes in ecosystems). (high school; earth's systems)

Each of these examples is (again) a very large and technical area of study, and the list could legitimately span much more. *What* exactly is meant to be assembled, and *what* knowledge is required for that to be possible?

III: Alignment with the Common Core Mathematics Standards

The link between science and math content is critically important, and any set of K-12 science standards should include explicit and direct references to mathematical content. To their credit, the NGSS authors acknowledged this important link and evidently worked to align the NGSS to the widely adopted Common Core State Standards for math (CCSS-M). Unfortunately, four problems arise in relation to that crucial alignment.

First, too often the NGSS references not the mathematics *content* in the CCSS-M, but rather the "mathematical practices" included therein. To be sure, there are important mathematical problem-solving skills that students need to master. But more important to the study of science is firm mastery of essential math content that provides the foundation for much of their science work, and the alignment between the math content and the science standards should be given far greater prominence.

Second, references to mathematics are often absent from the standards themselves, instead appearing only in the sections devoted to "Science and Engineering Practices," "Disciplinary Core Ideas," and/or "Crosscutting Concepts." The challenge is that these sections were taken nearly verbatim from the *NRC Framework* and include only general references to math, rather than specific content that students should learn. For example, the following appears under "Science and Engineering Practices":

> **Using Mathematics and Computational Thinking**
> Mathematical and computational thinking at the 9-12 level builds on K-8 and progresses to using algebraic thinking and analysis, a range of linear and nonlinear functions including trigonometric functions, exponentials and logarithms, and computational tools for statistical analysis to analyze, represent, and model data. Simple computational simulations are created and used based on mathematical models of basic assumptions. (high school; energy; forces and motion; interactions of forces; waves; engineering design; inheritance and variation of traits; space systems; and Earth's systems)

This is the only reference to "nonlinear functions" and is the closest the draft science standards come to acknowledging the existence and relevance of quadratic functions or equations. More detail about this critical math content is needed.

Similarly, the following passage from "Disciplinary Core Ideas" in the high school "energy" standards includes vague references to important math:

> Mathematical expressions, which quantify how the stored energy in a system depends on its configuration (e.g. relative positions of charged particles, compression of a spring) and how kinetic energy depends on mass and speed, allow the concept of conservation of energy to be used to predict and describe system behavior. (high school; energy)

Third, in some cases mathematics that is more advanced than can reasonably be expected at the grade levels for which it is indicated is called for or implied in the science standards, even in schools that faithfully impart the ambitious math specified in CCSS-M. This problem begins in the primary grades. For instance, the word "proportion" is used as early as grade two in the NGSS but does not show up until grade six in CCSS-M. Likewise, "relative abundance," a ratio in disguise, shows up before ratios do in CCSS-M. "Rates of change" are also mentioned often in the K-5 NGSS, but the obvious meaning of this phrase is not aligned with CCSS-M, where rates are not introduced until middle school.

The problem reappears in the draft science standards for middle schools which, for example, use correlation coefficients that CCSS-M doesn't introduce until high school.

And we find it again at the high school level. Take for example, these standards:

> Use mathematical, graphical, or computational models to represent the distribution and patterns of galaxies and galaxy clusters in the Universe to describe the Sun's place in space. (high school; space systems)
>
> Use mathematical representations of the positions of objects in the Solar System to predict their motions and gravitational effects on each other. (high school; space systems)

The first is an overreach for high school. It looks, rather, like graduate-student work in applied math or physics; and the standards should, at minimum, be more explicit about what mathematics they mean here. The second is difficult, but it is restricted to two bodies, which does not represent the Solar System well. Furthermore, rather sophisticated calculus is required to deal even with two bodies. More clarity as to the *actual* mathematical work required is needed here as elsewhere. But it is also a mistake for drafters to include (whether explicitly or implicitly) math in the NGSS that is more advanced than that set forth for corresponding grade levels in CCSS-M.

Fourth and finally, the opposite problem also arises, where the mathematics suggested or required by the NGSS is actually weaker than the content delineated in the CCSS-M. Radioactive decay, for example, is included in both the middle and high school NGSS. Studying radioactive decay requires the mathematics of exponentials and logarithms. The middle school standards do not specify any limitations on the math students should be expected to know. Yet, curiously, at the high school level, when more math could (and should!) be done, the standards *only* expect "graphical representations."

Similarly, one high school standard specifies that "Hardy-Weinberg calculations are beyond the intent of this standard." Yet the Hardy-Weinberg equation is just a very simple quadratic—one that students could reasonably be expected to do.

There may be a few instances where the math needed to learn science properly is different from what is found in CCSS-M. For example, statistics-of-error analysis and measurement error are critical to K-12 science standards. These standards should be clear extensions of (and meant to complement) the CCSS-M. Error analysis and measurement error are not specified in the CCSS-M but can be taught in science class. Where such situations arise, the NGSS drafters should be explicit and concrete about what else is needed.

In sum: Explicit mathematics is clearly not much on the minds of the drafters of these science standards. It should be. Math should not only be required as part of the K-12 science standards, but the standards should specify both precisely what math students should know as well as the limits of the math that students can be expected to do. And, as noted, alignment with CCSS-M is often absent. That is a serious drawback that calls for repair by competent mathematicians who are well versed in both sets of standards and can reconcile differences between them.

IV. Recommended Improvements

There *are* good standards to be found in this draft. We have already noted the solid handling of evolution within life science. There are other places where the choice of topic and/or the explicit or implied performance expectations are scientifically sound and grade appropriate. In physical science, for example, standards 2PP ("pushes and pulls") and 3.IF ("interactions of forces") make sense both as to content and placement within the K-12 continuum.

Here and elsewhere, the draft we reviewed is a start on a useful translation of the *NRC Framework* into creditable K-12 academic standards. *It only a start, however,* best seen as a conscientious and often painstakingly literal expansion of the organizational scheme and the heuristics of standards-writing in that framework. But that fealty to the *Framework* also means strong attachment to the weighting of science practices and crosscutting concepts (which the NRC itself viewed as "hypotheses") such that these now become as important as what has traditionally been called science knowledge or "content."

The drafters seem to have felt obligated to incorporate into every standard some explicit practice or action, such as "constructing" or "designing" or "investigating," as well as some reference—sometimes necessarily remote—to that new, fourth disciplinary core: engineering and applied science. These pressures make the language of the standards mechanical and repetitive. The repeated phrases are often clearly unrelated to the real meaning of the standard—namely some fact or idea of science to be learned and then deployed within contexts beyond the taught example. Perhaps most important, the overemphasis on practices and actions *is an irresistible invitation to soft, impressionistic assessments,* which would be an effect precisely opposite to the stated determination to *deepen* student learning. Imagine, for example, the problem of assessing honestly and objectively pupil performance vis-à-vis a standard in which the operative performance expectation is something like "model and communicate information about…."

Just as serious (and recurrent) a problem in this draft, as noted several times above, the quest for fewer standards has led to over-compression, overgeneralization, and omission. Much necessary "prior knowledge" to attain some standards is never supplied. Such omission is in some ways disingenuous, as it will require curriculum developers and teachers to fill in many gaps, *expanding* thereby the number of explicit standards and their breadth.

We have four suggestions for those who will be revising this draft:

> 1. Rewrite every standard to eliminate the "Practices" statements where they are empty, distracting, or not seriously assessable. Use Practices statements only when they have real content, and be clear in the text on how they are to be accomplished by the student *and how such accomplishment is to be assessed*.
>
> 2. Bring into the revision process a few *independent*, highly qualified scientists, i.e., individuals not previously involved with the drafting process, to check every standard in their special disciplines for errors and ambiguities (including assessment challenges), and to recommend corrections for any that they find.
>
> 3. For the indispensable parts of natural science that are mathematical and require the use of mathematics, get one or more consultants who are well-versed in *both the science and its component mathematics*, and who also know the CCSS-M, to revise the relevant standards so that they are properly aligned.
>
> 4. Put the next version of the standards themselves (with clarifications and other explanations as needed) into a single, clear, fully searchable document that can be read and used by state and district science specialists and by classroom teachers. The intricately interlocked web pages that we navigated (again and unfortunately, no longer online) are, in their way, beautiful. They may be appropriate accompaniments to a new standards release. But they do not lend themselves to application in the critical, final stages of curriculum design and classroom instruction at the district and school levels.

Finally, we repeat an important caution: The examples presented in Parts II and III are illustrative, not exhaustive. They are not intended as a working catalog of problems in this draft that need to be solved, seriatim. They do, however, illustrate the *kinds* of problems that forced themselves on the attention of all our reviewers.

Our purpose, however, is not to pose problems (although we have done so unavoidably). It is to help the NGSS process yield a final product worthy of widespread adoption. The science basics in the underlying *NRC Framework* were sound, as is a good deal of the science evident in this first draft of NGSS. Careful revision, with close attention to necessary but missing science, with elimination of content gaps and correction of mostly minor errors, with meticulous alignment to CCSS-M, and with honest expansion of the well-intended but unworkable "omnibus" standards, can yield a quality product, at least as good as the far-too-few outstanding versions that individual states have produced on their own.

[1] On this work, Achieve is partnering with the National Science Teachers Association and the American Association for the Advancement of Science, as well as the National Research Council.

[2] In fairness, Achieve requested comments on the draft by June 1—and pulled said draft from its website immediately thereafter. We admit to being three weeks tardy.

[3] Lawrence S. Lerner, Ursula Goodenough, John Lynch, Martha Swartz, and Richard Schwartz, *The State of State Science Standards 2012*(Washington, D.C.: Thomas B. Fordham Institute, January 2012). Available at: http://www.edexcellence.net/publications/the-state-of-state-science-standards-2012.html.

[4] National Center for Education Statistics, Nation's Report Card: Science 2011 (Washington, D.C.: Institute of Education Sciences, May 2012). Available at: http://nces.ed.gov/pubsearch/pubsinfo.asp?pubid=2012465.

[5] TIMSS and PISA results further prove this point. On the 2007 TIMSS science assessment, American eighth graders overall ranked eleventh out of forty-eight nations, with only 10 percent of American eighth graders scoring at or above the TIMSS "advanced" level. (By contrast, 32 percent of students in Singapore reached that level.) Similarly, the most recent PISA assessment, released in December 2010, showed fifteen-year-olds in the United States ranking a mediocre twenty-third out of sixty-five countries.

[6] Our review of the TIMSS assessment framework can be found here: http://standards.educationgadfly.net/timss/science2, and our review of the NAEP assessment framework is available here: http://standards.educationgadfly.net/naep/science3.

[7] Documents consulted for this review, once available on the Next Generation Science Standards website, are no longer accessible online. All subdocuments, along with the main standards document, were reviewed.

[8] Paul R. Gross, *Review of the National Research Council's "Framework for K-12 Science Education,"* (Washington, D.C.: Thomas B. Fordham Institute, October 2011). Available at: http://www.edexcellence.net /publications/review-of-the-nrc-framework-for-k12-science-education.html.

[9] It's important to recall that the authors of the *NRC Framework* acknowledged a few uncertainties. For example, they recognized that "the research base on learning and teaching the Crosscutting Concepts is limited. For this reason, the progressions we describe should be treated as hypotheses that require further empirical investigation."

[10] In this review, we did not systematically try to appraise what the *NRC Framework* appended—and NGSS drafters have embraced—as the fourth body of disciplinary content: "Engineering, Technology, and the Applications of Science." We intend to do so when reviewing future drafts of the NGSS. Our current concerns about that section are minor in comparison with those discussed here.

About the Authors

Paul R. Gross
Paul R. Gross was educated in Philadelphia public schools and at the University of Pennsylvania. He held a senior postdoctoral fellowship of the U.S. National Science Foundation at the University of Edinburgh, and was awarded an honorary doctor of science degree from the Medical College of Ohio. Now professor emeritus of life sciences at the University of Virginia, Paul Gross previously served as the university's vice president and provost, founding director of the Markey Center for Cell Signaling, and director of the university's Shannon Center for Advanced Studies. He is a fellow of the American Academy of Arts and Sciences, and has taught and directed research at New York University, Brown University, the Massachusetts Institute of Technology, and the University of Rochester (where he was chairman of biology and dean of graduate studies). He was director and president of the Marine Biological Laboratory, Woods Hole, Massachusetts, from 1978-88; a trustee of Associated Universities, Inc.; and a trustee of the American Academy of Liberal Education. The research of Dr. Gross and his students and fellows has centered on the molecular biology of development and cellular differentiation. His published works include numerous articles, essays, and books on topics ranging from fertilization and early animal development to contemporary issues in science, education, and culture. His most recent book (with philosopher Barbara Forrest) is *Creationism's Trojan Horse* (Oxford University Press, 1998).

Lawrence S. Lerner
Lawrence S. Lerner is professor emeritus in the College of Natural Sciences and Mathematics at California State University, Long Beach (CSULB). He was educated at Stuyvesant High School in New York, and the University of Chicago. A condensed-matter physicist by training, he is the author or coauthor of more than one hundred papers in that field and in the history of science, science and religion, and science education, as well as two university-level textbooks, an annotated translation of Giordano Bruno's *The Ash Wednesday Supper,* and a variety of book chapters and reviews. As former director of the CSULB General Honors Program, he reformed the curriculum, building it into one of strong interdisciplinary challenge. He was also the founding president of the university's Phi Beta Kappa chapter. He has authored or contributed to five earlier Fordham publications relating to state science standards and serves as associate editor of two scholarly journals. He lives in Woodside, California with his wife and two Newfoundland dogs. His interests include Renaissance music, opera, and gastronomy.

John M. Lynch
John M. Lynch (PhD, University College Dublin) has been at Arizona State University (ASU) since 1994 and specializes in scientific, theological, and cultural responses to evolutionary ideas. He is a principal lecturer and honors faculty fellow at Barrett, the honors college at ASU. He is also affiliated with ASU's Center for Biology and Society, the History and Philosophy of Science Program, and the graduate program in Human and Social Dimensions of Science and Technology. Since 1998, he has fought to maintain strong evolutionary principles in K-12 science standards. As such, he has presented on anti-evolutionism at many public, legal, educational, and scientific gatherings. He served as chair of the Educational Committee for the International Society for the History, Philosophy, and Social Studies of Biology between 2005 and 2011. Since 2007, he has also been a member of the Committee for Education of the History

of Science Society. Dr. Lynch has received a number of awards for his teaching and service including the CASE/Carnegie Foundation for the Advancement of Teaching Professor of the Year for Arizona (2007).

Martha Schwartz

Martha Schwartz has taught science and mathematics from seventh grade through early graduate school. She is also experienced in teacher training and professional development. She holds a bachelor's of science in mathematics from Arizona State University, a teaching credential from UCLA, a master's degree in geology from California State University, Long Beach, and a PhD in geophysics from the University of Southern California. She is a member of the Assessment Review Panel in science for the state of California and has worked on school improvement, standards, and testing for a variety of organizations.

Richard Schwartz

Richard Schwartz holds a bachelor's of science in chemistry from Arizona State University, a teaching credential from UCLA, and a master's degree in environmental science from California State University, Dominguez Hills. He taught secondary science for thirty-four years, the last thirty-two of them at Torrance High School in Torrance, California. He is a former member of the California Curriculum Commission and a 1995 recipient of the American Chemical Society's regional award in chemistry teaching. He retired from teaching in 2003, and recently retired from his second career at the University of Southern California, where he helped manage the geochemistry laboratory.

W. Stephen Wilson

Dr. Wilson is a professor of mathematics at the Johns Hopkins University where he has chaired the Department of Mathematics. In 2006, he was the advisor for mathematics in the Office of Elementary and Secondary Education at the U.S. Department of Education. Dr. Wilson also helped revise Washington State's K-12 mathematics standards and evaluated textbooks for the state. He has participated in numerous projects on standards, curricula, and textbooks and coauthored *Stars by Which to Navigate? Scanning National and International Education Standards* (Thomas B. Fordham Institute, 2009), *The State of State Math Standards* (Thomas B. Fordham Institute, 2005). More recently, he reviewed drafts of the Common Core Mathematics Standards for the National Governors Association and the Council of Chief State School Officers and coauthored *The State of State Standards—and the Common Core—in 2010* (Thomas B. Fordham Institute, 2010). Dr. Wilson received his PhD in mathematics from M.I.T. in 1972 and has published over sixty mathematics research papers in the field of algebraic topology.