Final Evaluation of the Next Generation Science Standards

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Foreword

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

Let us start with the bottom line: We know this Fordham report will be controversial, if only because so many have invested much time, treasure, and energy in the development of the Next Generation Science Standards (NGSS) and they urgently want these standards to be embraced throughout American K–12 education. We respect them, acknowledge their hard work, and honor their intentions.

Having carefully reviewed the standards, however, using substantially the same criteria as we previously applied to state science standards—criteria that focus primarily on the content, rigor, and clarity of K–12 expectations for this key subject—our considered judgment is that NGSS deserves a C.

Before you gasp or grump or lash out, let us remind you that, only a year ago, twenty-six state science standards received grades of D or F from our reviewers, while twelve also earned Cs. Just thirteen jurisdictions—one in four—had standards worthy of honors grades. Only seven earned grades in the A range. (You can see which in the table below.)

As is widely understood, weak standards are not the only—or the most worrisome—problem facing science education in the United States in 2013. Achievement in this field has been dismal. The most recent appraisals by the National Assessment of Educational Progress (NAEP, 2009) found barely one-third of fourth graders at or above the "proficient" level in science, followed by a mere 30 percent in eighth grade and an embarrassing 21 percent at the end of high school. Other studies have shown that just 30 percent of U.S. high school graduates are prepared for college-level work in science.[1]

By international standards, our performance in science is even worse. According to results from the most recent PISA assessment (released in 2010), fifteen-year-olds in the United States ranked twenty-third out of sixty-five countries. On the 2007 TIMSS science assessment, U.S. eighth graders overall ranked eleventh out of forty-eight nations, with only 10 percent of American students scoring at or above the TIMSS "advanced" level.

In short: American science education at the K–12 level needs a radical upgrade. And in our estimation, such an upgrade begins with dramatic improvements in the *expectations* that drive curriculum, teaching, learning, and assessment in this crucial realm. Evaluated against our criteria (spelled out in Appendix A), NGSS earned a higher score than the standards currently in place in twenty-six states (and they are clearly superior to the standards of at least sixteen of those states).[2] If schools in those states aligned their curricula and instruction to the NGSS, their students would likely be better off when it comes to science education.

[1] ACT, Inc., "The Condition of College & Career Readiness" (Iowa City, IA: ACT, Inc., 2011), http://www.act.org/research/policymakers/cccr11/readiness1.html.

[2] As we did in comparing the Common Core standards for English language arts and math with those of individual states, we believe that any state scoring two or more points higher on our 0-10 point rubric has standards that are "clearly superior" to the NGSS. Similarly, any state whose standards score two or more points lower than NGSS has

Jurisdiction	Grade	Score (out of 10)	Relative quality
California	A	10	clearly superior
D.C.	A	10	clearly superior
Indiana	A-	9	clearly superior
Massachusetts	A-	9	clearly superior
NAEP Framework	*A-*	*9*	clearly superior
South Carolina	A-	9	clearly superior
TIMSS Framework	*A-*	*9*	clearly superior
Virginia	A-	9	clearly superior
New York	B+	8	clearly superior
Arkansas	B	7	clearly superior
Kansas	B	7	clearly superior
Louisiana	B	7	clearly superior
Maryland	B	7	clearly superior
Ohio	B	7	clearly superior
Utah	B	7	clearly superior
ACT Framework	*C*	*6*	Too close to call
Connecticut	C	6	Too close to call
Georgia	C	6	Too close to call
Michigan	C	6	Too close to call
Missouri	C	6	Too close to call
New Mexico	C	6	Too close to call
Texas	C	6	Too close to call
Washington	C	6	Too close to call
NGSS	***C***	***5***	
Delaware	C	5	Too close to call
Florida	C	5	Too close to call
Minnesota	C	5	Too close to call
Mississippi	C	5	Too close to call
PISA Framework	*C*	*5*	Too close to call
Vermont	C	5	Too close to call
Alabama	D	4	Too close to call
Arizona	D	4	Too close to call

standards that are "clearly inferior." That means any state whose standards score *within* that range has standards whose relative superiority/inferiority is "too close to call." The NGSS earned 5 out of a possible 10 points. Hence any state whose standards earned 4, 5, or 6 is, in our view, "too close to call." Any state whose standards earned 0, 1, 2, or 3 has standards that are "clearly inferior" to the NGSS. In our state-by-state review of K-12 science standards, sixteen states earned a 0, 1, 2, or 3; therefore the NGSS are "clearly superior" to the standards governing teaching and learning in those sixteen states.

Jurisdiction	Grade	Score (out of 10)	Relative quality
Hawaii	D	4	Too close to call
Illinois	D	4	Too close to call
Maine	D	4	Too close to call
New Hampshire	D	4	Too close to call
North Carolina	D	4	Too close to call
Rhode Island	D	4	Too close to call
Tennessee	D	4	Too close to call
West Virginia	D	4	Too close to call
Colorado	D	3	Clearly inferior
Iowa	D	3	Clearly inferior
Kentucky	D	3	Clearly inferior
Nevada	D	3	Clearly inferior
New Jersey	D	3	Clearly inferior
Pennsylvania	D	3	Clearly inferior
Alaska	F	2	Clearly inferior
Idaho	F	2	Clearly inferior
Nebraska	F	2	Clearly inferior
Oklahoma	F	2	Clearly inferior
Oregon	F	2	Clearly inferior
South Dakota	F	2	Clearly inferior
Wyoming	F	2	Clearly inferior
Montana	F	1	Clearly inferior
North Dakota	F	1	Clearly inferior
Wisconsin	F	0	Clearly inferior

Having said that, by our lights the NGSS are inferior to the science standards of an almost equal number of states, and qualitatively on par with the expectations of a number of others. Students in those states would do better to be taught to the expectations of one of the states that have already done this really well. (Or to standards constructed upon the NAEP or TIMSS frameworks, both of which earned grades of A- from Fordham's reviewers.)

At day's end, of course, whether standards have *any* impact on achievement hinges on implementation and execution across the many moving parts of the education enterprise. Standards are just the beginning—a description of the goals to be attained, the destinations to be reached. They're not vehicles for getting there. Alas, we have long, glum experience with states whose standards look swell on paper but whose achievement is dreadful—because they never really operationalized their own standards. That could turn out to be as true of NGSS as of individual state standards.

One more crucial point at the outset: most states already have full plates of education reforms that are plenty challenging to implement, often including the Common Core State Standards for English language arts and math. Before undertaking any major change in their handling of science education, state leaders would be wise to consider whether they have the capacity to accomplish this in the near term, too. We caution against adopting any new standards until and unless the education system can be serious about putting them into operation across a vast enterprise that stretches from curriculum and textbooks to assessment and accountability regimes, from teacher preparation to graduation expectations, and much more. Absent thorough and effective implementation, even the finest of standards are but a hollow promise.

* * * * *

Background

From the very beginning, "standards-based reform" has depended on being able to articulate the knowledge, skills, and capabilities that students should acquire at various points along the K–12 path. Prior to the existence of state standards, the content that students learned and the expectations to which they were held varied, often wildly, from school to school, classroom to classroom, and district to district (not to mention state to state). And, perhaps unsurprisingly, it was our most disadvantaged students who typically ended up on the losing end, held to less rigorous standards that did not adequately prepare them for advanced coursework in high school, college, and beyond.

Prodded by *A Nation at Risk*, by the 1989 Charlottesville education "summit," by the governors' declaration of national education goals for the year 2000, and by several rounds of federal legislation, every state eventually undertook to develop its own academic standards in the core subjects of the K–12 curriculum. This, however, yielded a very mixed bag, with standards of varying degrees of quality and similarity, as has been evident in multiple expert reviews by the Thomas B. Fordham Institute over the past fifteen years—including three previous reviews of state science standards.

In part because so many state standards have been vague, content-light, and lacking in rigor, combined with mounting evidence from international sources that U.S. education is failing to keep pace with that of many other advanced countries, the standards conversation has shifted over the past five years or so. We no longer simply talk about setting standards, but rather of setting "college- and career-readiness" standards—academic expectations for the primary and secondary years that, if mastered, ensure that students are prepared to succeed in college and the modern workforce.

For English language arts and math, the Common Core State Standards (CCSS) sought to define "college- and career-readiness," and educators in forty-six states and the District of Columbia are striving (so far with varying degrees of commitment and success) to align their curricula, instruction, and assessments to these new—and often far more rigorous—expectations.

In the wake of CCSS, twenty-six states joined with Achieve to write college- and career-readiness standards for science. These "Next Generation Science Standards" (NGSS) were built upon a “Framework for K–12 Science Education” that was issued in 2011 by the National Research Council (NRC), and they aim to do for science what the Common Core did for ELA and math: to define the content and skills that all students—in multiple states—must master across grades K–12 in order to be fully prepared to succeed in college-level coursework and in modern jobs and careers.

The NRC Framework had many strengths. We asked the eminent biologist Paul Gross, a veteran Fordham reviewer, to evaluate it against our criteria for content, rigor, clarity, and specificity. Dr. Gross found that the Framework outlined much of the content needed to inform a rigorous K–12 science curriculum, that it was appropriately rigorous, and that the content progressed thoughtfully and deliberately through the grades.

Of course, the Framework was simply that: a high-level outline of the content and skills that students need to learn. As Dr. Gross explained in his review:

> The Framework is not… an actual set of standards, nor can it be so employed. It is meant to serve as a new and authoritative resource, setting forth indispensable principles, the most appropriate K–12 science content, and heuristic samples of good standards.

The NGSS authors then faced the considerable challenge of turning that outline into a set of clear and unambiguous standards, setting forth with completeness and specificity the actual content and skills that students need to learn to demonstrate understanding of the Framework’s core principles.

That job was made more difficult because the Framework faltered in *presenting* the principles, practices, and content of science. While much essential material was included, it was often difficult to navigate and “process” skills were given undue prominence. In the end, however, the Framework earned a B+ on the strength of the content that was presented. As Dr. Gross also noted:

> 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.

Unfortunately, that goal has yet to be realized. While the Framework was properly general, the NGSS needed to be thorough and concrete. Standards, after all, must clearly and unambiguously say what students need to know and be able to do. Without that, standards cannot succeed in setting a floor—or a destination—for curriculum, instruction, assessment, and accountability. Regrettably, the NGSS remain, in too many areas, as broad and general as the Framework they were meant to flesh out.

Evaluating the NGSS

We monitored the evolution of the NGSS through two public drafts, on both of which our reviewers provided extensive feedback and recommendations for improvement.[3] (See here for our comments on Draft I and here for our comments on Draft II.)

When the second of those drafts emerged in January 2013, we identified five significant flaws that we hoped would be fixed before the standards were finalized:

- Much essential content was omitted.
- The grade-to-grade progression that was a strength of the NRC Framework was not fully realized in the NGSS. The result was that some content that was never explicitly stated in earlier grades was nevertheless assumed in later grades.
- A number of key terms (e.g., “model” and “design”) were ill defined or inconsistently used and a number of actual errors were scattered throughout.
- Recommended “practices” dominated the NGSS, relegating essential knowledge—which should be the ultimate goal of science education—to secondary status.
- The articulation of “assessment boundaries” in connection with many standards threatened to place an unwarranted ceiling on important learning. Yes, teachers can go above and beyond what the boundary suggests, but with time and resources scarce, how many will actually teach students—even advanced students—content and skills that they know in advance “won’t be on the test”?

Now, the final NGSS have been released and states have begun to consider whether to adopt them. (Indeed, Rhode Island has already adopted the standards. Kentucky has moved in that direction as well.) So we asked our review team to evaluate the NGSS with fresh eyes.

Improvements First

The final version of NGSS incorporates some valuable improvements. For example, the “storylines” that introduce each grade level or grade band provide educators with welcome outlines of what the focus of learning will be. Our reviewers found that, at the elementary level in particular, “these storylines outline a clear and appropriate progression of learning from grade to grade.”

In addition, while early drafts of the NGSS presented engineering as a separate strand—one that seemed equal in importance to the core science disciplines—the final standards integrate engineering practices into the major scientific domains. This is as it should be: in K–12 classrooms, engineering ought not stand on its own, before students have a firm grasp of chemistry, physical science, and so on. (For more on the NGSS treatment of engineering, see page 51.)

We also recognize that the drafters faced tough choices in pursuit of their goal of K–12 science standards that are “fewer, clearer, and higher.” The failure to make such choices can lead to

[3] For complete bios of our review team, see Appendix B, *About the Authors*, on page 64.)

"kitchen sink" standards that then prove essentially impossible to implement. Our own understanding has benefited from the NGSS (and Common Core) efforts to set priorities, prune, and focus. We acknowledge in retrospect that our earlier reviews of California's standards, for example—in science and in other subjects—may have been too bullish because we admired their exhaustive treatment of content without fully appreciating the difficulty of actually transmitting so much in real schools and classrooms. This may be true of other state standards as well. Plaudits to NGSS and its authors (as well as to the NRC Framework authors and the CCSS framers) for facing up to the challenge of deciding what is most important for children to learn.[4]

Problems and Shortcomings

Below, we discuss at some length the NGSS's uncertain handling of college readiness and the standards' wrongful prioritizing of "practices" over knowledge. But three other problems need to be noted here (and are explained further in the report itself).

First, missing and "implicit" content. Pruning and prioritizing can be taken too far, and it does nobody any favors to pretend to omit content from one grade that later turns out to have been essential. Yet the NGSS sometimes does precisely that: it never explicitly requires some content in early grades that is then assumed in subsequent standards.

This problem is especially visible in the earth and space science section, where (in the review's words) "so much implied content is inferred in a single statement that it is difficult to imagine just what one might expect to be taught." Occasionally, in fact, "a standard appears which, by itself, introduces enough content to support an entire course." Standards should, as much as possible, clarify and prioritize what content and skills are essential at *each* grade level. By leaving so much to the whims of publishers, curriculum developers, and teachers—many of whom need specific guidance to help craft their scope-and-sequence plans and curriculum materials—we cannot be confident that all students in the schools and districts governed by the NGSS will learn what they need to be ready for college and careers.

Second, the risk posed by including "assessment boundaries" along with the standards. These are meant to cap large-scale assessments—to put a ceiling on the content and skills that will be measured at each grade—not to limit curriculum or instruction. The likely reality, however, is that such assessment limits will needlessly constrain what is taught and learned, particularly in advanced classrooms and for high-achieving pupils. The assessment boundaries articulated in the NGSS too often reduce the rigor or narrow the content of the standards when we could (indeed should) expect more. Take, for example, the following from high school life sciences:

> **HS-LS1-1. Construct an explanation based on evidence for how the structure of DNA determines the structure of proteins which carry out the essential functions of life through systems of specialized cells.** [Assessment Boundary: Assessment does not include identification of specific cell or tissue types, whole body systems, specific protein structures and functions, or the biochemistry of protein synthesis.]

[4] This is a matter of vigorous debate among our experts, some of whom believe that the California standards are clear, rigorous, and eminently teachable in an academic year. What is said here is the view of the co-authors of the foreword.

> **HS-LS1-2. Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms.** [Clarification Statement: Emphasis is on functions at the organism system level such as nutrient uptake, water delivery, and organism movement in response to neural stimuli. An example of an interacting system could be an artery depending on the proper function of elastic tissue and smooth muscle to regulate and deliver the proper amount of blood within the circulatory system.] [Assessment Boundary: Assessment does not include interactions and functions at the molecular or chemical reaction level.]

In both cases, the "boundary" limits assessments to vague generalities about core aspects of the life sciences and bars content that can and should be expected of high school students, and that might have been assumed as part of the curriculum if not for this unwarranted limitation.

Similarly, the assessment boundary in this middle school standard excludes three important topics that should provide a solid foundation for later chemistry study:

> **MS-PS1-5. Develop and use a model to describe how the total number of atoms does not change in a chemical reaction and thus mass is conserved**. [Clarification Statement: Emphasis is on law of conservation of matter and on physical models or drawings, including digital forms, that represent atoms.] [Assessment Boundary: Assessment does not include the use of atomic masses, balancing symbolic equations, or intermolecular forces.]

"Intermolecular forces" are the "bonds" between molecules that are formed and broken during a phase change (e.g., solid to liquid and liquid to gas and the reverse). Physical models can be weighed, taken apart, rearranged into products, and weighed again to clearly demonstrate the purpose of the standard and the excluded content as well.

Third, the failure to include essential math content that is critical to science learning. As our physics and chemistry reviewers explain:

> In reality, there is virtually no mathematics, even at the high school level, where it is essential to the learning of physics and chemistry. Rather, the standards seem to assiduously dodge the mathematical demands inherent in the subjects covered. There is math available in the Common Core that could be used to enhance the science of the NGSS. No advantage is taken of this.[5]

[5] Achieve has just released an appendix that describes the alignment between the NGSS and the Common Core math standards. A similar but incomplete appendix was released to accompany the second public draft of the NGSS. While we have not yet undertaken a thorough review of the new (and clearly more extensive) appendix, it's evident from the NGSS proper that some important math that is provided by the Common Core could be used to further science learning, particularly in the upper grades, but is given short shrift in these K-12 science standards.

The College-Readiness Quandary

Will a young person who learns what's spelled out in the NGSS truly be "college-ready"? The drafters say yes and state that a number of college and university professors agree with them.

Our reviewers remind us, however, that the answer to this question hinges on what one truly means by college-ready. Does it mean prepared to major in STEM subjects, or ready to grapple with "general education" science requirements? Ready to enter a vocational-technical program at a community college or to study chemistry at Wisconsin/Madison or MIT? To take a general "Intro to Science" course or the first course that chemistry professors would expect their serious chemistry students to take in college? These are widely disparate goals. The "front matter" for the NGSS explains:

> The NGSS do not define advanced work in the sciences. Based on review from college and career faculty and staff, the NGSS form a foundation for advanced work, but students wishing to move into STEM fields should be encouraged to follow their interest with additional coursework.

This explanation is insufficient. As this review was being completed, NGSS released additional guidance in the form of "Appendix K: Model Course Mapping in the Middle and High School for the Next Generation Science Standards." On the positive side, it acknowledges that STEM-bound students will likely need to—or opt to—pursue more advanced science study before college. Specifically, the Appendix says:

> It would certainly be recommended that students, especially those considering careers in a STEM-related field, would go beyond these courses to take science, technology, engineering, and mathematics courses that would enhance their preparation.

This is good to know—and corresponds to our analysis of NGSS—although it fails to say anything specific about what would need to be included in such additional "enhancement" courses beyond what's in NGSS.

More problematic, however, is that the content of NGSS itself fails to ensure that that *all* students will be equipped with sufficient content to make real the option of taking more advanced courses in the core STEM disciplines. This is particularly egregious in physics and chemistry, where our reviewers found that:

> …the physical science standards fail to lay the foundation for advanced study in high school and beyond, and there is so little advanced content that it would be impossible to derive a high school physics or chemistry course from the content included in the NGSS.

In this regard, Appendix K could even prove harmful because some of its suggested high school "course maps" imply that the NGSS include *all* of the content necessary for high school physics and chemistry courses. They do not.

This is especially troubling when one considers what many states require for high school graduation and many universities ask of their entering undergraduates. To pick a state we know well, Ohio's graduation requirements call for a minimum of three "units" of science during high school:

> One unit of physical sciences; one unit of life sciences; and one unit of advance (sic) study in one or more of the following sciences: Chemistry, physics or other physical science; Advanced biology or other life science; or Astronomy, physical geology or other earth or space science.[6]

If one then turns to the admissions prerequisites for Ohio State University, they stipulate "3 units of natural science with significant lab experience" and go on to note that "Students exceeding the minimum curriculum in math, natural sciences, or foreign language will be given additional consideration."

One assumes that these graduation and college admissions requirements are based on what is typically taught in high school physics and chemistry—content that, in the considered judgment of our reviewers, is largely missing from the NGSS. And so, by omitting essential content, yet signaling (via course maps) that NGSS *does* provide the basis for high school physics and chemistry courses, the authors have offered the country watered-down versions of heretofore more demanding courses in key STEM subjects. There is a real risk, then, that students in states that adopt the NGSS, or those that use the course maps to define learning in high school physics and chemistry courses, will graduate having taken courses that carry an impressive label but don't supply the requisite scientific content that the country urgently needs today.

Practices and Knowledge

Good science consists of doing as well as knowing, of practices as well as content and concept, and well-taught K–12 science has long understood and incorporated this truth. But doing it well requires a careful balance that seems somehow to have eluded the NGSS authors. Instead, they conferred primacy on practices and paid too little attention to the knowledge base that makes those practices both feasible and worthwhile.

This error is often and easily made by experts who themselves have long since learned the content and who see their fellow experts engaging in interesting practices on a regular basis because they, too, already possess the requisite knowledge.

But schoolchildren must *acquire* that knowledge in order to put it into practice. And their schools and teachers must make certain that this happens.

This is something that education pioneers like E. D. Hirsch, Jr. and cognitive scientists like Daniel Willingham have repeatedly and convincingly argued. "There is a consensus in cognitive psychology," Hirsch explains, "that it takes knowledge to gain knowledge."

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[6] "What it Takes to Earn an Ohio Diploma: Graduating Classes of 2014 and Beyond," Ohio State Department of Education, 2011, http://education.ohio.gov/getattachment/Topics/Academic-Content-Standards/Graduation-Requirements/What-It-Takes-to-Earn-an-Ohio-Diploma-2014-and-beyond-010711.pdf.aspx.

Even more critically, Willingham argues that “those with a rich base of factual knowledge find it easier to learn more—the rich get richer” and that

> factual knowledge [actually] enhances cognitive processes like problem solving and reasoning. The richer the knowledge base, the more smoothly and effectively these cognitive processes—the very ones that teachers target—operate. So, the more knowledge students accumulate, the smarter they become.

The purpose of K–12 science standards, therefore, is not primarily to encourage mastery of “practices” or to encourage “inquiry-based learning.” Rather, the purpose is to build knowledge *first* so that students will have the storehouse of information and understanding that they need to engage in the scientific reasoning and higher level thinking that we want for all students.

Unfortunately, the NGSS suffer from the belief—widespread among educators—that practices are more important than content. Consequently, every standard in NGSS articulates a practice first, even when doing so obscures the content that students should learn. And, while there are stand-alone standards that list practices and skills that students must master, there are no stand-alone expectations that list—in clear, teacher-friendly language—the content that students should learn. Throughout the NGSS, content takes a backseat to practices, even though students need knowledge before they’ll ever demonstrate fluency or mastery of scientific practices.

This is not the point of view of science Gradgrinds who believe that children must simply memorize and disgorge facts. Not at all. In fact, as Willingham recently observed:

> [I]f you mistake advocacy for a knowledge-based curriculum as wistful nostalgia for a better time, or as “old fashioned” you just don't get it. Surprising though it may seem, you can’t just Google everything. You actually need to have knowledge in your head to think well. So a knowledge-based curriculum is the best way to get young people “ready for the world of work.”

Indeed, this is the considered view of scientists and educators who have given high marks in the past to states that get the knowledge/practices balance right.

Consider South Carolina, whose science standards earned an A- from our review team a year ago. Each of the Palmetto State’s standards includes an academic content standard plus a series of “indicators.” These indicators not only help to specify the content that would otherwise be “assumed” by the broadly stated standard, but they also make clear what students need to do with the content they learn and what evidence will show that they have learned it.

In other words, the integration of content and essential processes in the South Carolina standards is seamless. The skills (i.e., indicators) actually support and extend the specific knowledge that students must learn to become scientific thinkers and writers. Consider, for example, this seventh-grade standard:

> The student will demonstrate an understanding of the classification and properties of matter and the changes that matter undergoes.

This statement—an obvious requisite for anyone who knows much of anything about science—is followed by ten indicators that make explicit both the content assumed in this standard as well as what students should be able to do with that knowledge. They are, for instance, expected to:

> "distinguish between acids and bases and use indicators (including litmus paper, pH paper, and phenolphthalein) to determine their relative pH."

and to

> "compare physical changes (including changes in size, shape, and state) to chemical changes that are the result of chemical reactions (including changes in color or temperature and formation of a precipitate or gas)."

Similarly, at the high school level, a physics standard states that:

> The student will demonstrate an understanding of the properties of electricity and magnetism and the relationships between them.

One of the eleven related indicators asks students to:

> Analyze the relationships among voltage, resistance, and current in a complex circuit by using Ohm's law to calculate voltage, resistance, and current at each resistor, any branch, and the overall circuit.

Again, these are not standards that encourage low-level thinking or rote memorization. They push student thinking while also being clear and specific enough to guide rigorous curriculum, instruction and assessment.

Some jurisdictions—the District of Columbia standing tall among them—got this balance right by clearly articulating the essential knowledge *and* the critical practices that students must learn. South Carolina went one better: it not only delineated content and practices, but also integrated "practices" with content—the stated goal of the NGSS authors. The NGSS tried hard but, in the end, went overboard on practices, particularly the kind that call for student attributes and activities that may have more to do with classes in writing, rhetoric, public speaking, art, even shop, than with scientific knowledge and understanding.

In Sum

As we noted in our comments on Draft II of the NGSS:

> …while nobody should be satisfied with our education system's overall performance in science, it's also important to keep in mind that when one sets out to overhaul that system, it's possible to make it even worse.

Yes, NGSS earned a higher score the standards in place in twenty-six states, and at least sixteen of those states have standards that are “clearly inferior” to the NGSS.[7] Yet twenty states have extant science standards that earned higher scores than the NGSS, including thirteen whose standards are “clearly superior” than what the NGSS offers.

* * * *

Where do states go from here? We have long advised leaders seeking to improve their standards to look to—and borrow from—other states that have developed clearer and more rigorous standards, as well as from sound national and international models and frameworks. Our advice here is similar. We encourage states that are dissatisfied with their present K–12 science standards to look to places like South Carolina and the District of Columbia, both of which are thorough as to content (without falling into the “kitchen sink” temptation) and serious as to rigor—but also do a fine job of amalgamating well-thought-out practices with that content. They have also developed strong support materials that, if implemented well, will drive curriculum and assessment development and instruction.

Also worthy of states’ renewed attention are the frameworks that undergird the TIMSS exams and NAEP assessments in science. Although not detailed grade-by-grade standards, they do an excellent job of describing the requisite content of a sound science education.

Such decisions are difficult, perhaps especially for states that have done a good job on their own. There are definite advantages to “common” standards, including comparability, portability, and some economies of scale. (Textbooks, for example, need not be customized to each state’s idiosyncratic standards and shared assessment instruments should be more economical than separate single-state procurements. The tests may be better, too.)

We at Fordham have long favored high-quality multi-state, even “national” academic standards, so long as they originate with, and are voluntary for, states. We’re bullish, for example, about the Common Core ELA and math standards because they are substantively strong and truly state-owned.

But “common” standards are not inherently superior to the work of individual states—and “improved” standards can come from multiple directions.

We will undertake in the near future to provide individual states with some additional information regarding the strengths and weaknesses of their current science standards in relation to those of NGSS. (We will also review the recently released Appendix L of NGSS, which maps

[7] As we did in comparing the Common Core standards for English language arts and math with those of individual states, we believe that any state scoring two or more points higher on our 0-10 point rubric has standards that are “clearly superior” to the NGSS. Similarly, any state whose standards score two or more points lower than NGSS has standards that are “clearly inferior.” That means any state whose standards score *within* that range has standards whose relative superiority/inferiority is “too close to call.” The NGSS earned 5 out of a possible 10 points. Hence any state whose standards earned 4, 5, or 6 is, in our view, “too close to call.” Any state whose standards earned 0, 1, 2, or 3 has standards that are “clearly inferior” to the NGSS. In our state-by-state review of K-12 science standards, sixteen states earned a 0, 1, 2, or 3, therefore the NGSS are “clearly superior” to the standards governing teaching and learning in those sixteen states.

the alignment between these standards and Common Core math.) In addition, Achieve promises a final appendix—one that will discuss "college- and career-readiness." We had hoped that this would emerge in time to incorporate into the present evaluation. But, because states are already beginning to make decisions about whether or not to adopt the NGSS, we wanted to share our impressions and evaluation of the K–12 science standards as published. They are, after all, the core of the work that Achieve and its partners have done and they do set forth the expectations that will drive K–12 science teaching and learning in states that choose to adopt them.

Acknowledgments

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We also deeply grateful to the content-area experts who have worked carefully and tirelessly—often under tight deadlines—to read, analyze, and comment on the Next Generation Science Standards: to Paul Gross, who ably led the team, as well as to our domain experts, Douglas Buttrey (engineering), Ursula Goodenough (life sciences), Noretta Koertge (philosophy of science), Lawrence Lerner (physical science, physics, and chemistry), Martha Schwartz (earth and space science), and Richard Schwartz (physical science, physics, and chemistry). Thanks also to William Schmidt and W. Stephen Wilson, both of whom have provided guidance and feedback on this review and will undertake a thorough review of the newly released Common Core Math-to-NGSS alignment appendix.

On the Fordham end, we are grateful to Michelle Gininger, Pamela Tatz, Matt Richmond, Joe Portnoy and the late Greg Hutko for their help in preparing the final report for publication.

Introduction and Overview

Paul R. Gross

I. Science Standards and Their Uses

> It is important to decide what scientific knowledge and skills all students should possess and to define them clearly. To do so, it is perhaps more important to decide whether standards should serve chiefly as baseline expectations for all students (i.e., as minimum competencies) or whether they should serve as a way to challenge the majority of our students to do better, even if all students cannot meet them.
>
> ~ Stan Metzenberg, Professor of Biology,
> California State University Northridge (2000)

This is our third Fordham review of the Next Generation Science Standards (NGSS), this one based on the official, final version of NGSS as released by Achieve on April 9, 2013. (Interested readers can find our feedback on earlier drafts here and here.) This review is the product of a nine-member team that includes practicing scientists and mathematicians, a distinguished engineer, and an historian/philosopher of science. All are experienced teachers of science and/or mathematics.

The final NGSS standards incorporate a number of changes from earlier drafts. We identify and discuss these below, recognizing changes that we find laudable (such as the new, introductory, grade-level "storylines") as well as those we find disquieting (primarily a further reduction of substantive science content). Then, using substantially the same criteria and scoring metrics as we applied earlier to reviews of state science standards,[8] we grade the NGSS. Our purpose here—and in state-specific comparisons that will follow—is to provide for state-level officials and science educators useful information as they consider adopting the NGSS and/or otherwise strengthening the science standards that are in poor repair in so many places.

Prior to reviewing the NGSS drafts, the Fordham Institute issued a review of the supporting document for these standards—a *Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, prepared under the aegis of the National Research Council.[9] As much will doubtless be made of the "alignment" of the NGSS with that Framework, it is important to underscore—as did the Framework's own authors—that it does not offer, nor need to offer, a full set of standards. Rather, it provided samples of standards appropriate to the

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[8] For example, see *The State of State Science Standards 2012*, Thomas B. Fordham Institute, 2012, http://www.edexcellence.net/publications/the-state-of-state-science-standards-2012.html.

[9] See *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, National Research Council, July 2011, http://www.nap.edu/catalog.php?record_id=13165; and Paul Gross, *Review of the National Research Council's Framework for K-12 Science Education*, Thomas B. Fordham Institute, September 2011, http://www.edexcellence.net/publications/review-of-the-nrc-framework-for-k12-science-education.html.

educational philosophy of its authors and responsive to the educational goals of its sponsoring and allied organizations. In its own words:

> …[This] Conceptual Framework for New K–12 Science Education Standards articulates the committee's vision of the scope and nature of the education in science, engineering, and technology needed for the 21st century. It is intended as a guide to the next step, which is the process of developing *standards for all students*…By framework we mean a *broad description of the content and sequence of learning expected of all students* by the completion of high school—but *not at the level of detail of grade-by-grade standards or, at the high school level, course descriptions and standards*. Instead, as this document specifies, the framework is intended as a guide to standards developers…[our emphases][10]

It follows that the guidance supplied by the Framework would not by itself provide adequate content coverage for a complete set of standards for K–12 science education. Hence in reviewing the Framework, we did not expect to see a comprehensive display of content standards. We did hope for a representative selection of important science topics, set forth with increasing sophistication, K-12 by grade or grade band.

Within those limits, we found the Framework on the whole an estimable product, and gave it a good grade. We were unimpressed, however, with the Framework's clarity and specificity, due to its heavy emphases on significant but nevertheless distracting peripheral recommendations—we called them ancillaries—and a preoccupation with pedagogical claims, speculations, and arguments, rather than with the content of science and the parts of it needing to be taught to today's students.

Turning to the actual NGSS standards grounded in the NRC Framework, we are mindful of the fundamental dilemma that inheres in the nature and mission of academic standards for primary and secondary education. As observed thirteen years ago by Professor Metzenberg (our epigraph), standards writers must somehow either deal with, or ignore, this real and necessary choice: are standards intended primarily to serve as a "baseline" for all students, or as an aspiration that many, perhaps most, but not all students will realize? Extreme positions on this choice have obvious limitations.

Professional science educators typically embrace one or the other of them enthusiastically, even passionately. They have been argued about, sometimes explicitly but often by indirection, slogan, and proclamation, for decades. The final version of the NGSS comes much closer to an explicit statement of purpose in this regard—and thus to acceptance of consequent limitations—than did its predecessors. The NGSS writers are explicit that these standards are intended to apply to the education of *all* students and they mince no words about their definition and use of *all*: they mean it to imply minimum required competencies—those performances that can reasonably be expected from *every* student. This goal is visible, not only in statements scattered through the document, but quite directly in the handling (or failure to handle) of high school physics and chemistry, as well as large tracts of high school biology and earth science. More on this point follows, below.

[10] *Framework*, 8.

II. The Centrality of Content

Cognitive scientists agree that one learns by building onto what one already knows. Some term this process of augmenting long-term memory "scaffolding." Concrete information is the base on which such scaffolds are erected, and concrete information—engagingly presented whenever possible—is what children love to acquire. It's also what they *must* acquire if they're to understand complex ideas or abstractions, or even just think about things successfully. In his seminal book, *Why Don't Students Like School: A Cognitive Scientist Answers Questions About How the Mind Works and What It Means for the Classroom*, University of Virginia psychologist Daniel Willingham explains it this way:

> Critical thinking is not a set of procedures that can be practiced and perfected while divorced from background knowledge. Thus it makes sense to consider whether students have the necessary background knowledge to carry out a critical thinking task you might assign.[11]

"Content" is how educators and standards-writers commonly describe the "information" and "facts" that comprise the *knowledge* part of education—and that make possible the conceptualizing, the thinking, and the doing parts. Content must be central to academic standards if curriculum developers, textbook authors, and classroom teachers are to know what students must learn and what must be taught to them. Suffice it, for the moment, to note that, K–12 standards must identify essential content explicitly, and in sufficient detail, for good teaching not only to be guided, but catalyzed.

What content should we expect a high school graduate to have encountered and to have learned about, say, the constituent elementary particles of matter, or the forces of nature, great and small? About the elements and their combinations in molecules and the behavior of molecules? About polymers and other macromolecules and their absolutely key roles in the manifestations of life? About the structures, the changes, the rise and fall of individual organisms and families thereof, of species, of biotic communities? About, indeed, the materials and structures of our rocky planet itself and the origins and transformations of those materials? About the cosmos upon which this planet is not even a pinprick? About the health and disease of individuals, certainly, but also of whole populations and of ecosystems—and as a result, of civilizations?

How are these bodies of knowledge subdivided and organized into the familiar disciplines and sub-disciplines of modern science and its main applications (such as engineering, technology, and medicine)? That vast, multidimensional matrix of knowledge is not only important, and more than just one of the great achievements of human history: it is also beautiful as a whole and in parts. Appreciation of such conceptual beauty is something to be taught. It is and can be taught and learned in school. Substantive content is—or in our view should be—the principal work of K–12 science education.

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[11] Daniel T. Willingham, *Why Don't Students Like School? A Cognitive Scientist Answers Questions About How the Mind Works and What it Means for the Classroom*, (San Francisco: Jossey-Bass, 2009), 37.

Our exhaustive examination of the science content in the NGSS showed it in some places to be adequate, in some places more than adequate—at times elegantly stated so as to make the work of users (curriculum makers, lesson plan makers, teachers) straightforward. In parts of some disciplines, the NGSS content is sequenced rationally and transparently, grade level by grade level. The early grades especially succeed in building those indispensable factual and theoretical scaffolds needed for the more sophisticated understandings of middle school content.

Therefore we take note, in general statements and then in detailed, standard-specific comments to follow, of such significant positives. They include, for example, some notable improvements appearing in the final version, such as the new "storylines" (brisk, sequential summaries of the succeeding grade's or grade band's standards). The integration of engineering practices with Disciplinary Core Ideas of science was originally troubled, but some valuable repairs have been made. In a summary statement on this topic, the engineering specialist of the review team notes:

> Many concerns with the integration of science and engineering in the previous NGSS draft have been addressed in this final release. The handling of issues related to energy forms and energy conservation is greatly improved, although a few concerns remain.

In other areas of content and at other grade levels, however, we often found content shortages and gaps, sometimes quite serious ones. (See the "Discipline-Specific Reviews" that follow for a fuller evaluation of the NGSS coverage of the core scientific disciplines.)

On balance, the final NGSS fail to deliver enough explicit content. Nor did we find, as the intended result of such content limitation, very many cases of increased depth—especially in comparison with the best current state standards. We found only some reductions of scope and eventually, at middle and high school levels, of sophistication, too, resulting from a systematic pruning of substantive content so as to make way for a vast expansion of science "practices."

III. Practices

All good science and science education incorporates practices of study, inquiry, and communications based solidly in knowledge and concepts. Other terms commonly used for practices include "skills," "applications," "processes," "activities," "inquiry learning," "hands-on," and so forth. Good state standards for K–12 science, such as South Carolina's, do an exemplary job of blending such practices with a steady acquisition of science content, determining which practices are best suited, and best learned, in connection with what content. Good standards maintain a careful balance that keeps the entire "practices" project within the grasp of assessment designers, teachers, students, and in general the classroom realities of time and space. What has begun to unbalance and ultimately to weaken science education in the current era, and is persistently visible in the NGSS, is a mounting animus toward content coupled with a near-fixation on practices.

A quarter of a century ago, one could already observe a reaction against what was said to be the old, outmoded pedagogy of science, which was (and is) characterized by K–12 science educators as memorization, facts (aka "factoids"), rote, and not much else. The time had come, they declared, for a new dispensation in the form of big changes to the teaching of mathematics and science. They would free the children from burdensome memorization, from algorithms, from mere information, from *vocabularies* they couldn't or needn't learn. Instead, the children would be empowered to learn science by *doing* it, doing what real scientists do—investigate, *inquire* into the workings of nature.

In any case, *mere* knowledge is widely held to be unnecessary in the digital age when we can get whatever facts we need at the click of a mouse. Dispensing with it would—we were told—liberate children and their teachers to investigate, to *inquire*. By means of "inquiry learning," we would—it was argued—reduce that mile-wide, inch-deep curriculum to something human-sized, and thereby make room for and enable in schoolchildren *evidence-based critical thinking*, understanding science in *depth.* Inquiry became the watchword of the first potential national standards: *Benchmarks* from the American Association for the Advancement of Science and the *National Science Education Standards* (NSES) proffered by the National Research Council two decades ago.[12]

As states began to write their own standards, strongly influenced by the NSES, many of them incorporated the then-new interest in science *processes*, that is, the *behaviors of scientific inquiry*, into their standards documents, commonly as sets of performance expectations separate from content. Those processes were cognitive (e.g., "scientific reasoning," the hypothetical-deductive method), social (e.g., speaking, writing, arguing about scientific issues), and physical (e.g., data gathering, data exchange and management, presentations).

Processes were soon consuming quite large parts of the time available for science. It is not easy to determine whether this large-scale change in pedagogy made any difference in the science performance of K–12 students. National and international assessments, anyway, have provided little or no evidence that American children have improved or are distinguished in the realm of inquiry.

Dissatisfaction rose as the country grew more concerned about its international competitiveness and employers declared that they could not find enough workers with suitable scientific and technological preparation. In the end, as exemplified by the NRC's Framework for the NGSS, science education planners and writers called for a major clarification of *inquiry*. Thus, in the Framework,

> …attempts to develop the idea that science should be taught through a process of inquiry have been hampered by lack of a commonly accepted definition of its constitutive elements. Such ambiguity results in widely divergent pedagogic objectives…an outcome that is counterproductive to the goal of common standards...[13]

The eventual clarification of inquiry consisted in the creation of a new dimension—one of three dimensions of equal weight—*each of which would be present in every* single *standard*. The new

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[12] *Benchmarks for Science Literacy* (Washington, D.C.: Oxford University Press, 1994); *National Science Education Standards* (Washington, D.C.: National Academy Press, 1996).
[13] *Framework*, 44.

dimension was dubbed *Science and Engineering Practices*. A second dimension, *Disciplinary Core Ideas* (DCI)—is the set of selected topics, i.e., the content—in each of the three traditional domains of school science (physical, biological, and earth and space science). The third, *Crosscutting Concepts* (CCC) is exactly what was called, in prior—even in the earliest—standards, "themes" or "big ideas."

In reviewing the Framework, we applauded the coupling of "practices" with substantive content. That is today a solid insight of cognitive psychology. As has been decisively shown, we think, and learn to think, best in reference to abundant and relevant factual knowledge—content—in long-term memory.[14]

Of practices as a part of science curriculum we have always approved, often with enthusiasm, so long as they didn't become a *substitute* for content, recognizing that evidence-based reasoning cannot be taught or learned in the absence of abundant domain-specific knowledge.[15] We watched with concern as the writers of the NGSS undertook to make a practice *integral to every standard for every DCI*. Indeed the practices—taking the form of some sort of action, activity, or behavior—introduce, lead, and often dominate all the standard statements, even though a DCI is also present. Many examples of this appear below. What we have observed as the optimum balance among content, concept, and practice has been turned on its head, with profound implications for the curricula, lesson plans, and assessments.

Insistent emphasis on practices (and crosscutting concepts) in *every* standard, on *every* disciplinary fact or idea, will probably introduce doubts, distractions, and uncertainties for all users of standards. This formal emphasis compromises severely the clarity and specificity that most conscientious educators expect to find in guidelines such as these. We readily grant that acquired good performance in the styles and habits of inquiry can enhance learning and stimulate students, but are they really assessable—and essential? And will the time, effort, and resources devoted to the performance—all to be found within the forty or fifty minutes per day that U.S. schools devote to science education—end by sapping the knowledge and understanding that were the educational objective in the first place?

To repeat: in earlier reviews of state, national, and international standards and frameworks for science education, *we have given high marks to well-balanced examples of practices incorporated into, even giving shape to, cognitive goals and scientific content.* In our view, the NGSS too often loses that balance.

IV. Assessment Boundaries (Limitations)

The NGSS (again following the NRC Framework) includes another problematic innovation: the provision of strong and explicit "assessment boundaries." Their ostensible and, in principle, reasonable purpose is to guide and control the grade-level sequencing of content. Applied as

[14] E. D. Hirsch, Jr., "Building Knowledge: The Case for Bringing Content into the Language Arts Block and for a Knowledge-Rich Curriculum Core for All Children," and Daniel T. Willingham, "How Knowledge Helps: It Speeds and Strengthens Reading Comprehension, Learning—and Thinking," *American Educator*, Spring 2006; see entire issue for more rich background.
[15] Willingham, *Why Don't Students Like School?*, 19-39.

intended, those boundaries are supposed to prevent distractions from the intended flow, for a given grade, of ideas and sophistication—distractions that would be caused by tests on subject matter deemed too difficult, too advanced, or too peripheral. The problem is that what is explicitly not to be tested will, in most cases, simply not be taught—and probably not be learned.

The assessment boundaries are therefore in effect a systematic *proscription* of difficult or advanced ideas. We have been told (verbally) that the assessment boundaries are intended to apply only to large-scale assessments such as those administered statewide. But we see no reason not to suppose that they will, in practice, also be applied to what happens within individual classrooms, curricula, schools, and districts. The difference is hardly trivial: official limitations on assessments are potential limitations on the richness and enterprise of curriculum content at the local level. This seems to us a particular problem for those charged with the education of better-prepared students who are ready, willing, and able to learn more science, and learn it faster or sooner—if only someone will teach it.

V. High School Science and College-Readiness

NGSS purports to chart the K–12 pathway to "college-readiness" in science. Here is what its introduction states:

> The current education system can't successfully prepare students for college, careers and citizenship unless we set the right expectations and goals…. Implementing the NGSS will better prepare high school graduates for the rigors of college and careers.

One of the NGSS background documents, describing the development process for these standards, also says this:

> Preliminary discussions with higher education faculty suggest that if students meet the Next Generation Science Standards (NGSS), they will be well prepared for college-level science courses.

In appraising NGSS, we were therefore obliged to assume that the drafters intended, and surely prospective users will take for granted, that these standards are intended to describe the science knowledge and skills that will prepare K–12 students for success in college science.

But what, exactly, is "college-readiness" in science? The authors of NGSS themselves seem unsure. For in its introduction, we also read that "These [core] ideas include the most fundamental concepts from chemistry and physics, but are intended to leave room for expanded study in upper-level high school courses." The newly-released Appendix K further explains that students, "especially those considering careers in a STEM-related field," should consider going beyond the content outlined in the NGSS and study more advanced science, technology, engineering, and mathematics courses.

Yet, the same appendix also suggests actual course sequences, using the content outlined in the NGSS that purport to cover high school physics and chemistry. By contrast, our reviewers found that the content delineated in the NGSS does *not* cover standard high school physics or chemistry, especially chemistry, but instead terminates (as far as the physical sciences are concerned) at the ninth- or tenth-grade level. This view is bolstered in chemistry, for example, by the absence of even the term *chemical equation,* let alone any statement that students should learn to write and balance such equations. Indeed, the only place in the entire NGSS document where the word *valence* occurs is at MS-PS1, where we read, “Assessment does not include valence electrons.”

It’s true that states and districts may opt not to require physics and chemistry of all students. It’s also true, however, that most state graduation requirements *do* require considerable study of science during high school, often two or three years of it. And it’s a fact that most admission requirements at four-year colleges either require or recommend the same thing.

Clearly, therefore, if the NGSS exclude *much of what has long been understood to represent high school physics and chemistry,* these standards will have to be supplemented with additional standards by the states adopting them. But that is what we have already! And *that* would appear to be contrary to the purposes of the present initiative. Students who take two or more years of science in high school are not a small, elite band of enthusiasts: they are many of those who graduate today and most of those who will take science courses in college, including future engineers, doctors, teachers, and scholars.

We are told that yet another forthcoming appendix will again address the issue of college-readiness. It will surely be better for the framers of NGSS to admit that it will need to be generously supplemented in order to achieve true “college-readiness.” But will those adopting and applying it read and honor such admonitions (if indeed they are forthcoming)? Will they parse a dozen appendices before developing their actual curricula and determining what to require of whom at what stage in the K-12 sequence? Or will they take for granted that what the NGSS actually set forth, if taught and learned, will indeed prepare students for college?

Summary

While there is much that troubles us about the Next Generation Science Standards, some important content is included in them and the elementary standards are typically stronger than those that follow for middle and high school. On balance, taking into account the evaluation of each of the core domains (physical science, life science, and earth and space science), along with the integration of science and engineering practices, we believe that these expectations deserve a 5 out of 10, when judged against our criteria.

That score is a composite, based on how the standards fared in two categories: content and rigor and clarity and specificity. Content and rigor are scored on a 0 to 7 point scale and clarity and specificity on a 0 to 3 point scale. The NGSS earned a 1.5 for clarity and specificity and an average score of 3.7 for content and rigor.[16] Added together, this earns the NGSS a 5.2 out of 10, or a C. (For a more thorough explanation of our grading, as well as our science-specific criteria and grading metric, see Appendix A on page 53.)

Conversion Table	
Grade	**Points**
A	10
A-	9
B+	8
B	7
C	5 or 6
D	3 or 4
F	0, 1, or 2

[16] For content and rigor, the NGSS earned a 4 for earth and space science, a 3.5 for life science, and a 3.5 for physical science (including physics and chemistry). This averages to 3.7 overall for content and rigor.

Organization of the Standards

The Next Generation Science Standards (NGSS) are presented two ways: by "topic" and by "Disciplinary Core Idea" (DCI).

When presented by topic, the standards are divided by grade level for grades K–5, and by grade band for middle school (6-8) and high school (9-12). Within each grade level or band, expectations are presented by large topic. In the physical sciences, for example, the five topics are: Matter and Its Interactions; Motion and Stability; Forces and Interactions; Energy; and Waves and Their Interactions In Technologies for Information Transfer. These topics are further subdivided into Disciplinary Core Ideas (DCIs). Under Energy, for instance, some of the DCIs are: Definitions of Energy; Conservation of Energy and Energy Transfer; and Energy In Chemical Processes.

When presented by DCI, the standards are organized similarly, except that within each grade level or band the expectations are grouped only by DCI.

Additionally, the NGSS provide a "storyline" at the beginning of each grade level, or, at the middle and high school level, at the beginning of each topic or DCI. These storylines broadly describe what students will study each year. In Kindergarten, for instance, the storyline explains:

> The performance expectations in kindergarten help students formulate answers to questions such as: "What happens if you push or pull an object harder? Where do animals live and why do they live there? What is the weather like today and how is it different from yesterday?" Kindergarten performance expectations include PS2, PS3, LS1, ESS2, ESS3, and ETS1 Disciplinary Core Ideas from the NRC Framework. Students are expected to develop understanding of patterns and variations in local weather and the purpose of weather forecasting to prepare for, and respond to, severe weather. Students are able to apply an understanding of the effects of different strengths or different directions of pushes and pulls on the motion of an object, so as to analyze a design solution. Students are also expected to develop understanding of what plants and animals (including humans) need to survive and the relationship between their needs and where they live. The Crosscutting Concepts – Patterns; Cause and Effect; Systems and System Models; Interdependence of Science, Engineering, and Technology; and Influence of Engineering, Technology, and Science On Society and the Natural World – are called out as organizing concepts for these DCIs. In the kindergarten performance expectations, for example, students are expected to demonstrate grade-appropriate proficiency in asking questions, developing and using models, planning and

carrying out investigations, analyzing and interpreting data, designing solutions, engaging in argument from evidence, and obtaining, evaluating, and communicating information. Students are expected to use these practices to demonstrate understanding of the core ideas.

Finally, the NGSS present “crosscutting concepts” for each DCI at each grade level. These set forth broad, general concepts (e.g., pattern, scale, quantity, proportion, system, and model) that are supposed to be common to—and “cut across”—all areas of science.

Clarity and Specificity

Strengths

The NGSS include many standards that clearly delineate what students need to know and be able to do, including the integration in some cases of altogether worthwhile "practices." Take, for example, the following high school standard for earth and space science, which gives clear and specific information about the critical content that students need to learn:

> **HS-ESS1-2. Construct an explanation of the Big Bang theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe.**

While our preference would be to specify the knowledge first, the following standard for third grade physical science nicely outlines what students need to understand, and the clarification statement gives additional guidance that would usefully guide curriculum development and instruction:

> **3-PS2-3 Ask questions to determine cause and effect relationships of electric or magnetic interactions between two objects not in contact with each other.** [Clarification Statement: Examples of an electric force could include the force on hair from an electrically charged balloon and the electrical forces between a charged rod and pieces of paper; examples of a magnetic force could include the force between two permanent magnets, the force between an electromagnet and steel paperclips, and the force exerted by one magnet versus the force exerted by two magnets. Examples of cause and effect relationships could include how the distance between objects affects strength of the force and how the orientation of magnets affects the direction of the magnetic force.] [Assessment Boundary: Assessment is limited to forces produced by objects that can be manipulated by students, and electrical interactions are limited to static electricity.]

Our reviewers also found that the new storylines add considerable value and that, particularly in the elementary years, they "outline a clear and appropriate progression of learning from grade to grade." In general, the storylines are more useful than the domain-specific introductions that are also provided. The high school storyline for earth and space science also clearly signals the interdisciplinary roots of that field of science:

> Students examine the processes governing the formation, evolution, and workings of the solar system and universe. Some concepts studied are fundamental to science, such as understanding how the matter of our world formed during the Big Bang and within the cores of stars.[17]

[17] Regrettably, the actual standards for high school earth and space science (discussed on page 46) fail to live up to the promise of that storyline.

Weaknesses

The highlights discussed above are, sadly, more the exception than the rule when it comes to clarity and specificity.

Overall, the standards are difficult to navigate and overwhelmed by vague performance expectations, all of which include "practices," even when their inclusion confuses rather than clarifies.

Even the document's organization is challenging to navigate. On a typical page, the performance expectations are listed at the top of a table, with three columns below. The central column presents the Disciplinary Core Idea (DCI). These are generally terse, but clearly written, statements describing some of the key concepts of the listed topics. The right-hand column includes "crosscutting concepts," which list broad, general concepts (e.g., pattern, scale, quantity, proportion, system, and model) that are supposed to be common to all areas of science. Crosscutting concepts, the authors explain:

> …can help students better understand core ideas in science and engineering. When students encounter new phenomena, whether in a science lab, field trip, or on their own, they need mental tools to help engage in and come to understand the phenomena from a scientific point of view.

In reality, however, too many of those concepts are so broadly generic as to offer no practical guidance for the classroom. For example:

> People's needs and wants change over time, as do their demands for new and improved technologies. (3-5-ETS-1)

> Phenomena that can be observed at one scale may not be observable at another scale. (MS-LS1-1)

Often, it's hard to understand how a crosscutting concept will help students access the related performance expectations. For example, a K–2 crosscutting concept explains:

> Patterns in the natural and human designed world can be observed, used to describe phenomena, and used as evidence. (K-LS1-1)

A related performance expectation asks students to:

> Use observations of the sun, moon, and stars to describe patterns that can be predicted. (1-ESS1-1)

How "recognizing patterns" will help students describe predictable patterns about the earth, moon, and sun is difficult to imagine.

The left-hand column is titled Science and Engineering Practices. Once again, these are frequently too vague to be useful. Take, for example:

> Make observations and measurements to produce data to serve as the basis for evidence for an explanation of a phenomenon. (5-PS1-3)

Or:

> Ask questions that can be investigated based on patterns such as cause and effect relationships. (3-PS2-3)

The performance expectations themselves are often poorly written and difficult to understand. They are also so broadly worded that a teacher would be hard-pressed to know not only what to teach, but at what depth. Take, for example, the following for Kindergarten:

> **K-PS2-2. Analyze data to determine if a design solution works as intended to change the speed or direction of an object with a push or a pull.**

What kind of data will a five-year-old child analyze? And is she expected to collect those data herself or will they be provided? What has this student been taught about "speed or direction"?

Worse still, by forcing a "practice" statement into every performance expectation, essential content is often obscured or buried. In fact, the performance expectations do not ask students to "know" anything. Rather they are required to: 1. Plan and conduct an experiment to…, 2. Make observations and measurements to…, 3. Ask questions to…, and 4. Define and design a device in order to….

While such activities can be pedagogically useful, they clarify neither the content that students need to learn nor the skills they need to master. Take, for example, the following:

> **4-LS1-1. Construct an argument that plants and animals have internal and external structures that function to support survival, growth, behavior, and reproduction.** [Clarification Statement: Examples of structures could include thorns, stems, roots, colored petals, heart, stomach, lung, brain, and skin.] [Assessment Boundary: Assessment is limited to macroscopic structures within plant and animal systems.]

Does "construct an argument" just mean "give examples"? And does it have more to do with science or with writing, rhetoric, and logic?

Similarly, the unnecessary and wordy "practice" at the beginning of this middle school performance expectation adds little value:

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

Is it more important that students "develop a model" or that they simply *know* the "changes in particle motion, temperature, and state of a pure substance when thermal energy is added or removed"?

A related problem: Clarification statements and DCIs often assume that content has been learned even when that content was never specified in earlier grades. For instance, the clarification statement for the middle school standard referenced above says that "molecules and inert atoms" are examples of the particles referred to. Yet, it's unclear whether students know which atoms are inert and that the discovery of these inert gaseous elements aided in the development and organization of the Periodic Table. Or whether they know why these atoms are inert and that one of these inert gases is the third most abundant element in Earth's atmosphere. Such prerequisite content is critical and should be specified in the standards themselves.

Taken together, the confusing presentation of the standards, combined with vague and poorly worded expectations, earns the NGSS a 1.5 out of 3 for clarity and specificity.

Discipline-Specific Reviews

Physical Science, Chemistry, and Physics

Overview

NGSS physical science coverage is mediocre throughout grades K–5. Sadly, its quality declines rapidly and steadily in middle school, and still further at the high school level, where little positive can be said. Indeed, the physical science standards fail to lay the foundation for advanced study in high school and beyond, and there is so little advanced content that it would be impossible to derive a high school physics or chemistry course from the content included in the NGSS.

Several salient issues permeate the entire physical science, physics, and chemistry section:

1. Minimal use (verging on intentional avoidance) of precise scientific vocabulary, often resulting in muddled meaning.
2. Omission of much basic prerequisite content.
3. The systematic underestimation of what students can learn, as evidenced by introduction of topics too late or avoiding them completely.
4. Omission of entire fields of physical science.
5. Too-frequent vague and poorly written standards that limit content to be tested. Specifically, "assessment boundaries" often exclude from consideration concepts at the heart of the subject in question, particularly where those concepts are best or necessarily expressed mathematically.
6. Indeed, we find a general absence (verging, again, on intentional avoidance) of mathematical relationships (formulas) and problem solving calculations. This shortcoming crops up at the middle school level and becomes critical in high school.

Physical Science

Content Strengths

As in other sections of NGSS, the storylines are valuable additions in physical science. Despite the occasional odd statement or contradiction, they provide a broad and useful outline. In the elementary grades, in particular, these storylines outline a clear and appropriate progression of learning from grade to grade. The first-grade storyline, for instance, explains:

> Students are expected to develop understanding of the relationship between sound and vibrating materials as well as between the availability of light and ability to see objects.

This is well elaborated in this first-grade standard:

> **1-PS4-1. Plan and conduct investigations to provide evidence that vibrating materials can make sound and that sound can make materials vibrate.** [Clarification Statement: Examples of vibrating materials that make sound could include tuning forks and plucking a stretched string. Examples of how sound can make matter vibrate could include holding a piece of paper near a speaker making sound and holding an object near a vibrating tuning fork.]

This is a fine, systematic expansion of the content that was introduced in Kindergarten, and the suggested student activities provided in the clarification statement will no doubt help students connect vibrating objects and sound.

The third-grade storyline takes advantage of the students' maturation, exposing them to important and somewhat abstract concepts, including action-at-a-distance forces in the physical sciences, and more generally, to complex systems where similarities and differences are not merely black and white. In fifth grade, the storyline introduces the student to several important ideas, including chemical changes (5-PS1-4), and in other fields, photosynthesis and the microscopic world (5-PS1-1).

Also at the elementary level, the standards (3-PS-2-2) make explicit reference to oscillating systems at a level appropriately higher than at their introduction in Kindergarten. And Standard 3-PS-2-3 nicely exposes students to electrostatic and magnetic (action-at-a-distance) forces.

The NGSS authors are also to be commended for making some important improvements from the previous draft. In first grade, for instance, expectations now include transparency, translucency, and opacity—important content that was previously neglected.

Content Weaknesses

While the strengths noted above are laudable, there too few of them over the wide K–5 range. And they are outweighed by weaknesses.

First, the NGSS physical science standards seem to go to great lengths to avoid integrating essential math content that would bolster them. At the middle school level, for example, it would be appropriate to introduce explicitly some simple mathematical apparatus and calculations. The absence even of very basic math conveys a false picture of modern natural science. But nowhere under Science and Engineering Practices is there any mention of such activity. (One sees it for the first time at the high school level, and there it is weak.)

The NGSS claim, in the Executive Summary, to be "aligned, by grade level and cognitive demand, with the … Mathematics Common Core State Standards." Being "aligned," however (assuming that is true), is not the same as *making use* within the science standards of math that (if the Common Core is properly taught) students will possess at the appropriate grade levels.

In reality, we found virtually no mathematics in the physical science standards, even at the high school level, where it is essential to the learning of physics and chemistry. Rather, the standards seem to avoid the mathematical demands inherent in the subjects covered.

A *second* troubling problem is that some topics are poorly covered—or omitted entirely—throughout the grades. Energy, and heat energy in particular, is a prime example of an important topic that is poorly addressed. Take, for example, the following middle school statement:

> PS3.A. The term "heat" as used in everyday language refers both to thermal motion (the motion of atoms or molecules within a substance) and radiation (particularly infrared and light). In science, heat is used only for this second meaning; it refers to energy transferred when two objects or systems are at different temperatures. (MS-PS1-4)

While it's appropriate to distinguish between the commonplace use of the term heat and its scientific use, this attempt is dead wrong. Heat does not mean radiation, though that is one of several mechanisms of heat transfer. While middle school might be too early to expose the student to a rigorous definition of heat, the groundwork must be laid so that, at the high school level, the student will be well prepared for the precise definition given by the first law of thermodynamics, $\Delta E = Q + W$, where ΔE is the change in internal energy of a system, W is the work done on the system, and Q is the heat energy added to the system. Unfortunately, this critical foundational content is absent.

What's more, the essential point is obscured within the standard: Heat is a mode of energy transfer. At a later grade, students can learn how this takes place on a microscopic level, but by middle school they ought to be using the term "heat" correctly.

Third, the NGSS also seem to shun precise scientific vocabulary, often resulting in muddled meaning. The storyline for middle school physical science, for example, asserts:

> Students also apply ideas about gravitational, electrical, and magnetic forces to explain a variety of phenomena including beginning ideas about why some materials attract each other while others repel. In particular, students will develop understanding that gravitational interactions are always attractive but that electrical and magnetic forces can be both attractive and negative.

Yet materials don't attract and repel each other; electric charges and magnetic poles do, and middle school science standards should be careful to use the kind of precise language that students need to build the knowledge they require. Also, "negative" is not the opposite of “attractive.” Replacing “negative” with “repulsive” would be both grade appropriate, and a proper introduction to a standard technical term.

Many more examples could be supplied.

Omissions

High school physical science content is virtually nonexistent. Entire areas that are fundamental to the understanding of physics and chemistry—and essential prerequisites for advanced study—are omitted. Among these are chemical formulas, chemical equations, the mole concept and its applications, kinematics, thermodynamics, and pretty much all of modern physics, including all of the advances of physics since about 1950, as well as their transformative engineering applications.

Nor is energy ever covered with adequate depth and rigor (as explained further below). The idea of building on earlier non-rigorous ideas of energy and making them rigorous at the high school level is glaringly absent.

“Static electricity” is mentioned only once and it’s not well explained or developed. “Current electricity” isn’t covered at all. These are serious omissions.

Missing, too, is content covering simple electric circuits, including voltage, current, resistance, their measurement, and Ohm’s law, $V = iR$, the relationship among them.

The middle school physical science storyline also states:

> Students will also … begin to develop an understanding of the relationship between force and energy.

Unfortunately, the expectations fail to introduce the fundamental concept of work, $W = Fx$, at the same time. If this were done, the path to a rigorous definition of energy at a later grade level would be made clear.

The common modes of heat transfer—conduction, convection, and radiation—are often introduced at or before fifth grade, and should certainly be introduced at the middle school level if not before. But only radiation is mentioned, and even that, as noted above, is defined misleadingly.

High School Chemistry

Overview

High school chemistry is largely absent from the NGSS. What little content is included is too often found in vaguely worded performance expectations that assume mastery of knowledge not previously introduced. The standards are further weakened by limitations found in the clarification statements and assessment boundaries, which place arbitrary caps on the knowledge and skills that will be assessed each year, as well as the near-total absence of mathematical relationships and problem solving, and the avoidance of appropriate scientific vocabulary.

Content Strengths

There's little to praise in the NGSS high school chemistry standards. At best, the Disciplinary Core Ideas on which the chemistry expectations are built are generally well-written and easily understood, though they rarely include the requisite content. What little content that is provided is, however, generally free from error.

Content Weaknesses

Besides the enormous swaths of chemistry content missing from the NGSS (see below), those standards that do appear are vaguely or confusingly written, fail to include appropriate scientific vocabulary, and assume mastery of content that was never previously required. Some also suggest activities that push the boundaries of what's safe and appropriate for K–12 students.

Many of these shortcomings can be seen bundled together in a single example. In Standard HS-PS1-3, students are asked to:

> **HS-PS1-3. Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles.** [Clarification Statement: Emphasis is on understanding the strengths of forces between particles, not on naming specific intermolecular forces (such as dipole-dipole). Examples of particles could include ions, atoms, molecules, and networked materials (such as graphite). Examples of bulk properties of substances could include the melting point and boiling point, vapor pressure, and surface tension.] [Assessment Boundary: Assessment does not include Raoult's law calculations of vapor pressure.]

The awkward writing is the least of the problems here. Students are asked to "compare the structure of substances" and relate this to the strength of "forces between particles." Unfortunately, the NGSS include no standards that address structure. The writers could have used this to introduce the Lewis dot technique that lends insights into molecular structure, but they didn't.

This standard also substitutes the vague "electrical forces between particles" instead of the simpler, more scientifically precise, "chemical bonds." Indeed, while the word "bond" does appear in a few places in the NGSS, it is never explained. And ionic and covalent bonding, the most common types, are missing entirely, as are the generally weaker but nevertheless important dipole-dipole and hydrogen bonding. (Indeed, dipole-dipole bonding is specifically excluded by the clarification statement for this standard, despite its importance and grade-appropriateness.)

This standard incorrectly lists "networked materials (such as graphite)" as a particle, but that's wrong. Graphite is a flat (two-dimensional) macromolecule, composed of carbon atoms that are bonded together by strong covalent bonds.

Also problematic are some of the experiments suggested to study properties. Determining the boiling temperature of almost any liquid can be extremely dangerous, as most common liquids other than water are flammable. Measuring vapor pressure and surface tension quantitatively is very difficult to do and requires special equipment not usually available in high school labs.

Omissions

As noted in the physical science section (above), much foundational, prerequisite chemistry content is missing entirely from NGSS. Among the most important omissions are concepts such as writing and naming chemical formulas, ions and their charges including polyatomic ions, atomic number, atomic mass and molar mass, and acid/base/pH/neutralization.

A computer search failed to turn up a large number of terms usually used in high school chemistry. In most cases, the concepts are missing entirely; in a few cases, they are danced around with alternative vocabulary, as though euphemisms were necessary in teaching chemistry to youngsters.

The following is a partial list of important high school chemistry content that is missing entirely from the NGSS (with the exception of endothermic and exothermic reactions, which are poorly addressed but not named in the standard HS-PS3-1):

- electromagnetic spectrum/color,
- metric system/SI/units,
- endothermic/exothermic reactions,
- molecular/structural formulas,
- chemical bonding to include ionic/covalent/metallic/hydrogen bonding, single, double, and triple bonds,
- nonmetals/semimetals,
- solution terminology like concentrated/dilute/solute/solvent/soluble/insoluble/types of solutions/ preparation and concentration calculations, molarity,
- atomic models (e.g., Bohr, quantum theory),
- Ideal gas law and its simple math,
- oxidation/reduction,
- types of named chemical reactions like decomposition, precipitation, synthesis, and single and double replacement,
- titration,
- formula writing and naming of compounds,
- acid/base chemistry including pH,
- writing and balancing chemical equations,

- the mole concept and chemical arithmetic (stoichiometry),
- organic chemistry,
- electrochemistry,
- properties of elements with explanation.

Quantum theory is missing despite the fact that it is *the* accepted model of the atom. Understanding a little about the quantum model of the atom helps students explain the order of elements on the periodic table, as well as the strength of bonds, atomic emission spectra, and the geometry and properties of molecules.

Throughout the NGSS, clarification statements are added to help clarify precisely what students should know and be able to do. Yet many of these clarification statements assume mastery of prerequisite content that was never covered in the NGSS, and nowhere are these gaps more evident than in chemistry. As in all of science, chemistry should build from simple to complex. A standard in this field should not start with "atoms are conserved" and expect to get students to the point of balancing complex chemical equations automatically and using them to predict and calculate quantities of reactants and products, yet the NGSS assumes precisely this leap. There is a sequence of topics that must first be understood: from atoms to elements, to symbols, to molecules, to compounds, to chemical formulas, to coefficients and subscripts, and finally to equations and balancing and mole/mass calculations. Nearly all of those pesky little steps are left out of the NGSS. They need to be included—and they need to be specific and clearly written, using the appropriate vocabulary.

High School Physics

Overview

Nothing in NGSS might form a basis for the standard high school physics course, much less preparation for an "advanced" course in physics.

The storyline for high school physical science tells us that students will:

> …continue to develop their understanding of the four core ideas in the physical sciences. These ideas include the most fundamental concepts from chemistry and physics, but are intended to leave room for expanded study in upper-level high school courses.

It is impossible, however, to reconcile this statement with the underlying principle that NGSS is intended to cover the entire K–12 student experience. Is the standard high school physics course an "upper-level high school course"? If that is so, NGSS comes to a screeching halt at the end of ninth grade, so far as physics is concerned.

Content Strengths

We cannot discourse on the strengths of material that is absent.

Content Weaknesses and Omissions

Here are the most important subjects that are essential to a high school physics course but absent from NGSS:

1. Kinematics. Without a grounding in kinematics, not even a semiquantitative understanding of Newtonian dynamics (Newton's laws of motion, etc.) is possible.
2. A rigorous approach to defining and using the concept of energy. The vital principle of conservation of energy cannot be understood without a progressive, quantitative broadening of energy concepts.
3. Thermodynamics and a simple approach to its basis in kinetic theory. And, subsidiary to this, a survey of heat engines. (Thermodynamics has vital applications in chemistry as well.)
4. Modern physics. There should be at least a mention of elementary particles (e.g., leptons, mesons, bosons, quarks). The developments of the twentieth century should not be omitted.
5. Last but certainly not least, the broken promise of cross-reference to and use of the Common Core math standards, which constitutes a serious flaw at the middle school level, becomes a fatal omission here.

The treatment of Newtonian dynamics is a pedagogical farce, asking students to:

> **HS-PS2-1. Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.**

Here, the concept of "acceleration" appears for the first time, yet $F = ma$ is conspicuously absent. And one wonders how a student is meant to "analyze data" without having learned the kinematic relation $x = ½ at^2$?

Throughout the document, the definition of *field* is limited to this vague DCI:

> Forces at a distance are explained by fields (gravitational, electric, and magnetic) permeating space that can transfer energy through space. (PS2.B)

But in fact student understanding of the rather abstract idea of field can readily be facilitated by defining field in terms of force, which the student already understands; e.g., "The electric field E at any point in space is the force exerted on a charge q at that point divided by q; $E = F/q$." At this introductory level, it is a serious pedagogical error to "explain" concrete forces in terms of abstract fields rather than vice versa.

Ampère's and Faraday's laws are introduced by implication but never named—and certainly never expressed mathematically:

> … provide evidence that an electric current can produce a magnetic field and a changing magnetic field can produce an electric current. (HS-PS2-5)

It will be no surprise that no mention is made of such fundamentally important bases of modern society as the electric generator and motor, whose operation cannot be understood without Ampère's and Faraday's laws.

As for energy, the high school physical sciences storyline claims:

> The Core Idea expressed in the *Framework* for PS3 is broken down into four sub-core ideas: Definitions of Energy…

Unfortunately, this promise is not fulfilled. In Standard HS-PS3-1, the closest approaches to a definition are two, both inadequate and unsatisfactory at this level. The first is in an assessment boundary:

> **HS-PS3-1.** Assessment is limited to basic algebraic expressions or computations; to systems of two or three components; and to thermal energy, kinetic energy, and/or the energies in gravitational, magnetic, or electric fields.

But this is really a listing of energy types rather than a definition. A second definition comes in DCI PS3.B:

> PS3.B. 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. (HS-PS3-1)

While this hints at how one might make the distinction between potential and kinetic energy, there is not a single mention of the fundamental concept of work, which underlies the entire formalism that leads to a real definition of energy via the work-energy theorem. Here again, a golden opportunity for pedagogy is missed: Work is a concrete, readily understood concept (e.g., in the restricted elementary definition $W = Fx$) while energy is somewhat abstract.

There is no mention at all of the structure of matter at levels below electrons, protons, and neutrons; nothing about semiconductors and the revolution they have made possible, or of lasers (despite their ubiquity in everything from CD players to supermarket checkouts).

Finally, as mentioned in the chemistry section (above), the word quantum occurs exactly once, and in the negative context:

> **HS-PS4-3. Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than the other.** [Clarification Statement: … Examples of a phenomenon could include resonance, interference, diffraction, and photoelectric effect.] [Assessment Boundary: Assessment does not include using quantum theory.]

Yet one wonders how students are to discuss the photoelectric effect in a non-quantum context?

Life Sciences

Overview

While there are notable exceptions, treatment of the life sciences is generally solid in elementary school, but grows thin by middle and high school. Too much important content is represented only by mere mention or allusion within "omnibus" standards that refer to large bodies of content for which either necessary precedent in lower grades or needed detail is missing. Worse, serious gaps in cellular and very basic molecular biology content are evident, and some excellent opportunities for integrating engineering and technology are missed, even though the life sciences offer obvious and currently important possibilities—as in biotechnology.

Content Strengths

In two active and important areas, the life science content is to be commended. First, considerable, reasonably detailed attention is given to key features of ecosystems, communities, elementary cycles, and ways in which all of these can be and are disrupted—and repaired. Similarly, the standards addressing evolution are better organized and generally stronger than in many of the state standards that we have reviewed. This is important because evolution-centered ideas continue to reinforce such major sub-disciplines of biology as ecology, embryology, and physiology.

The middle school life science units also include strong sections on the common ancestry of animals based upon a range of morphological criteria and data.

Content Weaknesses

At the middle and high school levels, the content covered by the NGSS is systematically biased against "difficult" subject matter.

Thus, for example, *even the most elementary biochemistry is given short shrift* (not really surprising, considering the general and widespread neglect of chemistry in the NGSS, noted elsewhere in this review). Inadequately treated are molecules small and large, cell biology, genetics, and elementary mechanisms at the cellular and gene levels of morphogenesis and development.

Here is an example from cell biology and genetics: the high school treatment of meiosis. That process is flatly identified as "cell division." That is easy; it saves quite a lot of detail, some of it slightly complicated—but it is wrong. In the course of meiosis, the pro-gametic cells do *divide*. But they do not divide by the ordinary process commonly referred to as "cell division" (or mitosis), which is the doubling, then the equipartition, of the chromosomes followed by the creation of two identical nuclei from the original one. Thereafter comes cytokinesis, which divides the whole cell body into similar or identical *daughter cells*.

Nor is meiosis just a process in which chromosomes may sometimes (merely) "swap sections." The power of meiosis is far greater: via the process called independent assortment, it creates enormous genetic variation. The mechanism resides in the cytological details, which are easily, in fact, diagrammed and taught. They *must* be understood if the meaning of sexual reproduction in plants and animals, and its role in evolution, is to be understood to any depth. In the NGSS we are supposed to be shooting for depth, rather than superficial breadth.

Similarly, the expectations addressing organisms and heredity are weak. Both are heavily dependent on molecules, including macromolecules, their chemistry and assembly, and interactions. Yet, in contrast to the considerable space given to explanations of ecosystems, explanations at the molecular levels of biology are terse and highly incomplete. Further weakening these standards, assessment boundaries indicate that the chemical-molecular domains are *not* to be included in assessments of student understanding.

One high school standard, for one example, expects from the student "…a model to illustrate the hierarchical organization of interacting systems that provide specific functions…" of (physiological) systems, but includes an assessment boundary that explicitly eliminates from assessment "interactions and functions at the molecular or chemical reaction level."

Pity the classroom teacher who is supposed have some serious notion of what would constitute an adequate "model" in this case. It is hard to imagine a professional development program that will actually equip teachers to visualize *models* that *illustrate* hierarchical organization of *systems*, let alone to assess and grade them conscientiously and well. Pity the curriculum or assessment designer who needs to decide *what*, in this typically *practices*-driven standard (remember, the expected performance is the creation of *a model*…), is actually to be taught and tested about the vast (implied) body of requisite *knowledge*.

Yet students who have no familiarity with the basic molecular features of DNA, proteins, subcellular organelles, gene transmission, and the regulation of gene expression, and whose grasp of biochemistry is limited to vague notions of carbon and energy flow—whether or not college- or science-committed—will be poorly prepared for twenty-first-century encounters with health and disease. They will also be ill-prepared to grapple with life science issues of high public interest: genetically modified crops and foods, cloning, stem-cell therapies, the character and uses of genetic counseling, individualized therapeutics, environmental toxins.

Perhaps such content is meant simply to be assumed, as in a typical "omnibus" high school standard which asks students to "communicate scientific information that common ancestry and biological evolution are supported by multiple lines of empirical evidence," and where the clarification statement insists that:

> **HS-LS4-1**. Emphasis is on a conceptual understanding of the role each line of evidence has relating to common ancestry and biological evolution. Examples of evidence could include similarities in DNA sequences, anatomical structures, and order of appearance of structures in embryological development.

Yes; that much covers an entire unit, at least, of a full high school biology course. Here, though, knowledge of DNA base sequences and their use in determining evolutionary relationships, which *is*, in fact fundamental to the modern understanding of this subject, is merely suggested, not required.

Similarly, one Disciplinary Core Idea explains:

> LS4.A. Genetic information, like the fossil record, provides evidence of evolution. DNA sequences vary among species, but there are many overlaps; in fact, the ongoing branching that produces multiple lines of descent can be inferred by comparing the DNA sequences of different organisms. Such information is also derivable from the similarities and differences in amino acid sequences [of proteins with the same function in different species…which would be needed to upgrade this allusion to relevant knowledge!] and from anatomical and embryological evidence. (HS-LS4-1)

But in the standards, a minimalist, allusive approach to heredity and modern phylogenetics, which must include meiosis and some basic Mendelian genetics, results in confusion and disinformation. (See also below, under *Errors*.)

Indeed, the general treatment of heredity, vital as it is to modern evolutionary science, is weak in NGSS, especially as regards the basics of genetics, nucleic acids (DNA and RNA) and, more generally, the dramatic contributions of molecular biology that began to revolutionize the life sciences in the 1950s.

Omissions

"Omnibus" standards, of which there are many, are the real problem of omission. There are several examples in which NGSS standards assume that extensive content is or will be taught, but never provide the necessary *prior* standards or backup. Take, for example, the middle and high school coverage of physiology. In middle school, students are asked to:

> **MS-LS1-3. Use argument supported by evidence for how the body is a system of interacting subsystems composed of groups of cells.** [Clarification Statement: Emphasis is on the conceptual understanding that cells form tissues and tissues form organs specialized for particular body functions. Examples could include the interaction of subsystems within a system and the normal functioning of those systems.] [Assessment Boundary: Assessment does not include the mechanism of one body system independent of others. Assessment is limited to the circulatory, excretory, digestive, respiratory, muscular, and nervous systems.]

This task is vast and mysterious. How is a student to understand interactions between systems without understanding something of each system on its own? Where and when will that have been learned? Doesn't one need to understand circulatory and kidney function in order to understand how the kidney filters blood? Is the circulatory system a system or a subsystem? The standards should be clear and explicit to ensure that this critical information is neither glossed over nor omitted. Furthermore, without specifying the missing content, what does all this high-level generalization contribute to an understanding of any physiological topic "in depth?"

Examples abound of this overly compressed "omnibus" treatment of cellular-chemical-molecular relations. Here is another from physiology:

> **HS-LS1-2. Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms.** [Clarification Statement: Emphasis is on functions at the organism system level such as nutrient uptake, water delivery, and organism movement in response to neural stimuli. An example of an interacting system could be an artery depending on the proper function of elastic tissue and smooth muscle to regulate and deliver the proper amount of blood within the circulatory system.] [Assessment Boundary: Assessment does not include interactions and functions at the molecular or chemical reaction level.]

How are they to understand elasticity (for example) in this context without at least mention of the key elastic protein (elastin) and how it works and what it looks like? Functions at the "organism system level" *entail* functions at the cellular, subcellular, and molecular levels. There is nothing in NGSS to indicate that students are expected to have anything but vague notion of how cells and their components—mitochondria, cell membranes, cell walls, etc.—work; ribosomes don't even get a mention. Moreover, there is just a sentence stating that unicellular organisms exist, and, except for noting that bacteria are "decomposers," bacteria are absent from this entire document. Yet they are the most abundant and ecologically important organisms on the planet. There is also no mention of viruses.

The very terms, and hence simple but important concepts, of prokaryote and eukaryote cellular life are absent. With all such detail omitted, the "hierarchical" systems demanded can be only the simplest kinds of flow diagram, knowledge that, in the end, violates the stated purpose of the pervasive emphasis on *practices*. If, that is, a standard like this refers to content by allusion, and the required content is a series of simple formalisms without detail, then that content can be learned only by—memorization.

In fact, many of the standards provided are written so as to emphasize and encourage various forms of communication about *high-level abstractions* or loose generalizations. Once again, pity the curriculum and assessment writers, not to mention teachers, who will be expected to grade in a meaningful way student work based upon such standards as the many that begin like this: "Develop and use models of _______ to support explanations of _______ patterns in _______. (MS-ESS2-e)

Errors

There are quite a number of mostly-small errors in the NGSS life science expectations, some of which will mislead teachers and students. See, for example, "meiosis," above.

At the middle school level, we're also told:

> PS3.D. Cellular respiration in plants and animals involves chemical reactions with oxygen that release stored energy. In these processes, complex molecules containing carbon react with oxygen to produce carbon dioxide and other materials. (MS-LS1-7)

This is misleading. The relevant processes are oxidations and reductions; but this has fundamentally to do with the transfer of electrons to molecules like NAD and not reactions with oxygen in the usual, commonly recognized sense. The role of oxygen is to serve as terminal electron/proton acceptor in the electron transport chain, *during which ATP is produced*. That last is the most important point. In any case, this is an inadequate rendering, even for middle school, of the fundamental, universal process of cellular respiration, explaining nothing.

One last example. We read that "Each chromosome pair contains two variants of each of many distinct genes." This may or may not be true for some loci but it is most certainly *not* true for all. A clear, specific treatment of genetics would not fail to discuss homo- versus heterozygosity. Homozygous loci have two copies of a single "variant."

Earth and Space Science

Overview

The NGSS earth and space science standards are fairly ambitious in their scope, particularly at the secondary level, and much of the essential K–12 content that students need to learn to be college- and career-ready is included—or at least implied. Unfortunately, perhaps as a consequence of the desire to cover so much, too many standards become rather long laundry lists of content. Worse still, essential prerequisite knowledge is too often missing from the standards in earlier grades, leaving too much assumed and too little explicitly stated.

Content Strengths

The strongest feature of the NGSS in earth and space science is its inclusion of many important topics. Students will be introduced, for example, to important theories for the origin of the universe and of the solar system:

> **HS-ESS1-2. Construct an explanation of the Big Bang theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe.**

The above is an especially nice example because it includes study of the evidence trail leading to the theory.

Similarly, the following outlines essential elements of K–12 earth and space science study.

> **HS-ESS1-6. Apply scientific reasoning and evidence from ancient Earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history.**

Content Weaknesses

Unfortunately, the chief strength of the earth and space science standards also contributes to its greatest weakness: the NGSS places large quantities of sometimes-disparate science into one statement, often without proper background from earlier grades. Sometimes so much content is implied in a single statement that it is difficult to imagine just what one might expect to be taught (or to have been taught previously). At times, a standard might even introduce enough content to support an entire course. One such expects students to tackle interactions between complicated systems:

> **5-ESS2-1. Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact.** [Clarification Statement: Examples could include the influence of the ocean on ecosystems, landform shape, and climate; the influence of the atmosphere on landforms and ecosystems

> through weather and climate; and the influence of mountain ranges on winds and clouds in the atmosphere. The geosphere, hydrosphere, atmosphere, and biosphere are each a system.] [Assessment Boundary: Assessment is limited to the interactions of two systems at a time.]

And another:

> **HS-ESS2-3. Develop a model based on evidence of Earth's interior to describe the cycling of matter by thermal convection.** [Clarification Statement: Emphasis is on both a one-dimensional model of Earth, with radial layers determined by density, and a three-dimensional model, which is controlled by mantle convection and the resulting plate tectonics. Examples of evidence include maps of Earth's three-dimensional structure obtained from seismic waves, records of the rate of change of Earth's magnetic field (as constraints on convection in the outer core), and identification of the composition of Earth's layers from high-pressure laboratory experiments.]

The model of the layered Earth was not developed in earlier grades, so the idea of Earth having a core and a mantle is newly introduced here. Density is introduced earlier, as an observed property, but it needs to be understood somewhat more quantitatively here. The fact that Earth has a magnetic field is newly introduced here, too, when students need to consider *changes* to it.

Besides all this new basic content, the standard also asks students to understand seismic waves and how they are used to map the planet's interior. This involves distinguishing the different kinds of waves and how they reflect and refract at boundaries. We also find in this standard the "composition of Earth's layers" in a sequence which omitted basic material on rocks and minerals. This standard presents an excellent piece of accessible solid-earth geophysics—if only it had the proper scaffold.

A fourth-grade standard asks students to:

> **4-ESS3-2. Generate and compare multiple solutions to reduce the impacts of natural Earth processes on humans.** [Clarification Statement: Examples of solutions could include designing an earthquake resistant building and improving monitoring of volcanic activity.] [Assessment Boundary: Assessment is limited to earthquakes, floods, tsunamis, and volcanic eruptions.]

But how does a student even contemplate an earthquake-resistant building or the monitoring of a volcano without first understanding how those phenomena work?

And in middle school:

> **MS-ESS3-1. Construct a scientific explanation based on evidence for how the uneven distributions of Earth's mineral, energy, and groundwater resources are the result of past and current geoscience processes.** [Clarification

Statement: Emphasis is on how these resources are limited and typically non-renewable, and how their distributions are significantly changing as a result of removal by humans. Examples of uneven distributions of resources as a result of past processes include but are not limited to petroleum (locations of the burial of organic marine sediments and subsequent geologic traps), metal ores (locations of past volcanic and hydrothermal activity associated with subduction zones), and soil (locations of active weathering and/or deposition of rock).]

The trouble with this is that it is the first mention of most of these complicated processes. Formation and trapping of petroleum is a big deal involving a lot of chemistry and structural geology and stratigraphy; ores depend on some knowledge of volcanic processes including hydrothermal activity and what occurs in subduction zones. This appears to be the only occurrence of the string "subduct" in the whole document.

Perhaps the touchiest (and, in terms of understanding current policy disputes, perhaps the most useful) element of the earth and space science standards is their inclusion of expectations that address climate change. One of the relevant standards appears in an ambitious high school standard dealing with natural resources:

> **HS-ESS3-5. Analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth systems.** [Clarification Statement: Examples of evidence, for both data and climate model outputs, are for climate changes (such as precipitation and temperature) and their associated impacts (such as on sea level, glacial ice volumes, or atmosphere and ocean composition).] [Assessment Boundary: Assessment is limited to one example of a climate change and its associated impacts.]

Leaving aside the policy controversy, this standard is too much, too sudden, too complicated, and too advanced, given the weak background provided by the standards up to this point. To be able to deal competently with this content at the high school level, students must already have acquired at least an elementary feel for the chemical composition and physical structure of the atmosphere; its transparency (or not) to electromagnetic radiation at various wavelengths; blackbody radiation (dependence on temperature); mechanism of greenhouse effect in general; heat budgets, which include sensible heat as well as heat stored as latent heats (evaporation and freezing); specific heats of various earth materials and their reflectivity; pH, especially of ocean water; unstable isotopes for dating and stable ones for signals from ice and sediment cores; and many other matters, including an introduction to the methods used in computer models. High school students *could* certainly deal with all those at an appropriate level and acquire an elementary but realistic sense of "climate science," but this has to be developed coherently over time. Very little such development is visible in these standards.

Errors

The earth and space science standards themselves are relatively error-free, but here's one from physical science that applies especially to the Earth:

> PS4.A. Waves, which are regular patterns of motion, can be made in water by disturbing the surface. When waves move across the surface of deep water, the water goes up and down in place; it does not move in the direction of the wave except when the water meets the beach. (Note: This grade band endpoint was moved from K–2). (4-PS4-1)

While there is no net transport of water in a deep-water surface wave, the particle motion is roughly circular and not just vertical. This is critical because, without the horizontal component, there is no reason for the observed direction of water at the beach (caused by frictional drag against the bottom). Students can just as easily learn that the water moves in circles.

Omissions

Though a great deal of content is touched upon or alluded to or taken for granted in the earth science portions of the NGSS—indeed, as noted above, very large amounts are sometimes amassed into single, overwhelming standards—there are some missed opportunities as well. The absence of an elementary section on minerals and rocks means that students will grapple with the changes to the Earth's surface without having necessarily learned what the surface is made of and how its materials cycle. There is, as well, a general inattention to the basic *mechanisms* of earth processes. For example, references are made in various places to earthquakes and volcanoes, their presence at plate boundaries, and the fact that they constitute hazards. But there is not enough attention to what earthquakes and volcanoes fundamentally *are*, why they happen, how they work, how they are measured and described, and what about them might be dangerous—or sometimes beneficial. The NGSS also misses an opportunity to use the history of plate tectonic theory as an illustration of how scientific thinking develops. What data and reasoning went into this important and recent paradigm shift?

Some good content that we saw in the second NGSS draft was removed in the last round of editing. A worrying example was a strong former item about rocks and minerals and the cycling of rock materials:

> **MS-ESS2-g. Collect data and generate evidence to answer scientific questions about the chemical and physical processes that form rocks and minerals and cycle Earth materials.** [Clarification Statement: Investigations can use various materials to simulate the processes of melting, crystallization, weathering, deformation, and sedimentation. These processes act together to cycle and recycle Earth materials.]

Also now missing, important in light of its relationship to of climate change, is the only reference to the workings of the greenhouse effect:

> **MS-ESS2-n. Use models of Earth's atmosphere and surface to support the explanation of the greenhouse effect.** [Clarification Statement: Model explanations, physical or conceptual, reveal various ways that heat energy moves through and is stored within Earth's systems.] [Assessment Boundary: The rates of energy absorption by different reservoirs and their effect on the radiation balance of the system are not assessed. A complete understanding of the electromagnetic spectrum is not assessed.]

Engineering, Technology, and Applied Science

Whereas earlier public drafts of the NGSS presented engineering standards as a separate strand, the final standards now integrate engineering and technology components with the scientific Disciplinary Core Ideas. This was an important and constructive alteration. While it is important to include engineering and technology in the NGSS, it is even more important that K–12 students see engineering in the context of science content and application and that they first master the critical discipline-based content so that they will be able to understand and engage in engineering. Indeed, the best way to prepare for college-level engineering is to master basic prerequisite science content while considering how that content can, in many cases, be put to use through design activities.

We find, for example, this laudable general engineering design objective in HS-PS3-3:

> **HS-PS3-3. Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy**.

This is worth doing, but to be practicable it needs to be accompanied by more specifics on goals and constraints.

It's also good to see this in HS-PS4-5:

> **HS-PS4-5. Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.**

Still, the NGSS contain a number of clear weaknesses that bear on engineering, often arising from the missing content noted elsewhere in this review. The dearth of critical chemistry content organized and presented sequentially through the grades, for example, is apt to mean that entering college students will not have a sufficient foundation on which to learn and apply chemical engineering.

As indicated in the life science review (see page 41), the NGSS ignore several opportunities to integrate life science and engineering. Indeed, the only engineering and technology evident in that section is associated with biodiversity and ecosystem management, or with ethical issues bearing on genetic modification of organisms. Activities involving growth of simple organisms such as algae or yeast could have been included to study how nutrients, light, and other factors can be controlled to achieve engineering design goals such as capturing energy or preparing food. While it is important to avoid inappropriately contrived attempts to label activities as engineering- and technology-related, this should not mean their near exclusion from an entire area.

Finally, as also noted elsewhere in this review but important to underscore in relation to engineering, students who do not take focused chemistry and physics courses in high school will not be ready for college-level study in the "T" or "E" of STEM any more than in the mainline disciplines of science. The NGSS content expectations in and of themselves do not supply that background.

Appendix A: Methods, Grading Metric, and Criteria

Methods

This review examined the quality, content, and rigor of the final draft of the Next Generation Science Standards. We sought to determine how clearly, specifically, and rigorously they cover important content in four areas: physical science (including physics and chemistry), life science, earth and space science, and science and engineering "practices." In addition, we considered how well engineering practices were integrated with the content outlined in each of the core scientific disciplines (although we did not specifically "score" engineering within NGSS).

While in the course of this review we considered all materials that Achieve had released as of June 2013, the focus of our analysis was on the standards themselves—those presented by Disciplinary Core Ideas that include "science and engineering practices," grade-specific performance expectations, and "crosscutting concepts." (At the time of publication, Achieve had not yet released Appendix C, which is promised to discuss "college- and career-readiness.")

In carrying out this review, our reviewers used substantially the same content-specific criteria (see below) that were developed for our reviews of state K–12 science standards, *The State of State Science Standards in 2012*. The NGSS were evaluated against these content-specific grading criteria and judged against the same grading metric (also below). To increase inter-discipline comparability, the common grading metric used for our analyses of state, national, and international K–12 science standards (including this review) is the same as was used in Fordham's 2010 review of mathematics and English language arts standards, *The State of State Standards—and the Common Core—in 2010*, as well as our 2011 review of states' U.S. history standards, *The State of State U.S. History Standards 2011*.

The final score is a composite, based on how well the NGSS fared in two broad categories: content and rigor; and clarity and specificity. Content and rigor are scored on a 0 to 7 point scale and clarity and specificity on a 0 to 3 point scale. The final score is the sum of these two sub-scores. That final score was converted into a letter grade according to the following scale (again the same as was used for our evaluation of state K–12 science standards):

Grade	Points
A	10
A-	9
B+	8
B	7
C	5 or 6
D	3 or 4
F	0, 1, or 2

Content-Specific Criteria and Common Grading Metric

As described above, our experts developed criteria that delineated the essential content that should be included in rigorous, K–12 science standards. Those criteria follow.

Introduction to the K–12 Criteria

In an effective standards document for K–12 science, instruction in the proposed content from Kindergarten through eighth grade should proceed with increasing sophistication and abstraction, as appropriate to grade. This progression is suggested in the staged content expectations below.

Science cannot be taught effectively without carefully designed and content-matched laboratory and field activities to augment textual materials. Students' understanding of science processes and scientific discourse depends in an essential way on such activities. Laboratory work with well-designed instruments and tools—already available or thoughtfully designed and purposefully built for tasks that students can readily understand—is also an indispensable path to understanding relationships between science and technology and the values of good design. But standards themselves need not name specific laboratory work related to each idea; this may be done in related curriculum documents.

It is impossible to specify an absolute, minimal, "must-have" set of content items in K–12 for all modern science. Physics, chemistry, biology, geology, astronomy, and other sciences are intellectually distinct in important ways, but they are also interdependent and overlapping in others. Quantitative thinking and problem-solving are critical in all. Science content choices for the first eight years of schooling should include basic and unique topics from all three of the now-standard domains: physical, life, and earth and space science. The sequence of presentation may vary, and some areas may be omitted in some years, but this essentially arbitrary tripartite division has come into near-universal use. It is certainly how most schools, states, and universities organize their expectations for K–12 science.

<u>Science Content: General Expectations for Learning through Grade Eight</u>

Physical Science

- Know and be able to describe the common forms and states of matter, including solids, liquids, and gases, elements, compounds, and mixtures.
- Know how to use the standard units of measurement (SI).
- Understand time rate of change and the relationships among displacement, velocity, and acceleration.
- Understand the relationship between force and motion and be able to solve elementary problems in mechanics.
- Know how to define "gravity."

- Understand kinetic and potential energy, and their transformations.
- Know that matter is made of atoms, which are made of still smaller particles, and that atoms interact to form molecules and crystals.
- Know that heat is a mode of molecular motion. Understand temperature and explain how a thermometer works.
- Know some of the evidence that electricity and magnetism are closely related.
- Know the parts of a simple electric circuit and be able to build one.
- Recognize that light interacts with matter, as in such phenomena as emission and absorption.

Earth and Space Science

- Describe the organization of matter in the universe into stars and galaxies.
- Describe the motions of planets in the solar system and recognize our star as one of a multitude in the Milky Way.
- Recognize Earth as one planet among its solar system neighbors.
- Describe the internal layering of Earth by composition and density.
- Identify the sun as the major source of energy for processes on Earth's surface.
- Describe the main features of the theory of plate tectonics, and cite evidence supporting it.
- Understand how plate tectonics contributes to re-shaping Earth's surface and produces phenomena such as earthquakes, volcanism, and mountain building.
- Identify common minerals by their observable properties.
- Know the major rock types and how the rock cycle describes their formation.
- Understand weather in terms of such basic concepts as temperature and air pressure differences, humidity, and weather fronts.
- Distinguish between weather and climate, and describe changes in Earth's climate over time.
- Describe the hydrologic (water) cycle.
- Recognize that sedimentary rocks and the fossils they may contain preserve a record of conditions at the time and place in which they formed.
- Explain that the Earth environment supplies indispensable resources for humans (e.g., soil), but also creates hazards (earthquakes, volcanic eruptions, floods). Understand that human activity can protect the environment or degrade it.

Life Science

- Know requirements for the maintenance of life, short- and long-term, including food, appropriate environment, and efficient reproduction.
- Know how to identify, describe clearly, and name some plant and animal species, including our own.
- Identify the broadest physical and chemical characteristics of Earth's biota.
- Show familiarity with structure and function in pro- and eukaryotic cells and in the tissues of multicellular organisms.
- Know the elements of biological energetics, including cellular respiration and photosynthesis.

- Trace major events in the history of life on Earth, and understand that the diversity of life (including human life) results from biological evolution.
- Identify and describe the basic stages of gamete formation and embryogenesis in animals.
- Understand Mendel's laws, phenotype, and genotype.
- Recognize that genes are made of nucleic acids and encode the structure of proteins.
- Recognize the significance of differential gene expression in the processes of development.
- Know the operations of some biochemical and physiological systems (e.g., digestive, sensory, circulatory) in microbes, plants, and animals—including humans.
- Be able to offer examples of cooperation and competition among plants and animals in groups, in populations, and in ecosystems.

Science Content: General Expectations for Learning for Grades Nine through Twelve

Between ninth grade and high school graduation, some students take just one science course, whether an integrated course ("general science") or a single discipline such as biology. College-bound students typically take two or three science courses, and "STEM"-minded students are likely to take three or four, including advanced study in one or several of the core disciplines of science. Elective opportunities, including AP courses, abound in many high schools. The expectations below include content that we would expect *all* students to learn as part of a basic "integrated" science course, as well as content that would lay the foundation for, and become part of, high school courses in physics, chemistry, biology, and so on. They do not, however, attempt to set forth all the content that students would take in "advanced" classes (such as AP) in those subjects.

High School Physical Science (Including Physics)

- Use Newton's laws quantitatively to describe falling bodies, linear and curvilinear motion, simple harmonic motion, and fixed-axis rotation.
- Describe planetary motion using Kepler's laws and explain how those laws derive from Newton's laws of motion.
- Use momentum and energy conservation laws to describe one-dimensional elastic collisions.
- Use the work-energy theorem to explain the constancy of total mechanical energy in a frictionless system (e.g., a bouncing superball).
- Understand and describe the absolute temperature scale, the Celsius and Fahrenheit scales, and be able to convert from one to another.
- Explain the first law of thermodynamics in terms of the concepts of heat flow, work, and internal energy.

- Use the operation of an idealized heat engine/heat pump to explain the concepts of thermodynamic efficiency and coefficient of performance. Evaluate the efficiency of heat engines and the performance of refrigerators.
- Understand and be able to apply basic electromagnetic quantities, including charge, polarity, field, potential, current, resistance, capacitance, inductance, and impedance.
- Understand simple electric and electronic circuits quantitatively, in terms of currents and voltage drops.
- Understand how electromagnetic radiation results from the interaction of changing electric and magnetic fields. Analyze refraction and reflection at an optical interface.
- Recognize the basics and some applications of spectrometry.
- Describe the photoelectric effect and the production of X-rays.
- Describe elementary particles; distinguish matter and radiation.

High School Physical Science (Including Chemistry)

- Outline the Bohr and quantum mechanical models of the atom, and relate them to spectral lines and electron transitions. Understand and give examples of the role of ionic, metallic, covalent, and hydrogen bonding in chemical and biochemical processes.
- Be able to use Lewis dot structures to predict the shapes and polarities of simple molecules.
- Use kinetic theory to describe the behavior of gases (the ideal gas law) and phase changes.
- Understand and apply the basic principles of acid-base and oxidation-reduction chemistry.
- Understand the common factors that affect the rate of a chemical reaction, e.g., catalysis.
- Describe dynamic equilibrium processes as ones in which forward and reverse reactions occur at the same rates and how a system at equilibrium reacts when stressed.
- Write and balance equations for chemical reactions, and solve stoichiometric problems using moles and mole relationships.
- Understand the role of carbon in organic chemistry; write structural formulas for simple aliphatic and aromatic compounds, and name them correctly.
- Calculate the concentration of solutions (as molarity and percent) and discuss factors that affect solubility.
- Use the periodic table to discern and predict properties of atoms and ions, and the likelihood of chemical reactions taking place among them.

Earth and Space Science

- Cite and explain evidence that the universe has been evolving over some fourteen billion years.
- Describe important events in Earth and solar system evolution over the past four billion years.

- Explain the main events in the evolution of stars and how a star's initial mass determines its eventual fate.
- Know the main physical characteristics of solar system planets and their major satellites.
- Understand and use correctly the basic units of astronomical distance.
- Explain methods of relative and absolute dating of rocks.
- Explain why earthquakes occur, how their sizes are reported as intensity and magnitude, and how scientists use data to locate an earthquake's epicenter.
- Summarize the main lines of evidence for the existence and motion of tectonic plates.
- Describe the movement of continents in terms of mantle convection, lateral motion, seafloor spreading, and subduction at the boundaries between plates.
- Show where Hawaiian-style and Vesuvian-style volcanoes are located in relation to plate boundaries and mantle hot spots, and compare their eruption styles and the structures they build.
- Describe climate and weather patterns in terms of latitude, elevation, oceans (with reference to special properties of water, such as specific heat), land, heat, evaporation, condensation, and rotation of the planet.
- Describe the greenhouse effect and how a planet's atmosphere can affect its climate.
- Describe the solar cycle. Be aware of possible effects of solar activity variation on planet Earth.
- Describe how nutrients such as carbon cycle through the atmosphere, hydrosphere, and solid earth.

Life Science

- Describe the differences between prokaryotes and eukaryotes and probable evolutionary relationships between them.
- Describe ultrastructure and functions of the principal subcellular organelles.
- Understand the distinctions between asexual and sexual reproduction.
- Identify landmark stages of mitosis and meiosis, the purpose of meiosis, and key stages of early development and morphogenesis in animals.
- Be able to state and apply Mendel's laws and to recognize their operation in genetic crosses.
- Know the basic structures of chromosomes and genes down to the molecular level.
- Know the principal steps in photosynthesis, its contribution to the evolution of Earth's atmosphere, and its effect on the forms and chemistry of green plants.
- Understand the genetic code and the steps by which it is expressed in protein synthesis.
- Provide evidence to support the central role of differential gene expression in cellular differentiation and development, e.g., the role of Hox genes.
- Compare and contrast structure and function of basic physiological systems in animals and higher plants, e.g., digestive, circulatory, sensory, reproductive.

- Define natural selection and speciation in terms of population and evolutionary genetics.
- Understand how evolutionary relationships are inferred with the help of gene/genome sequencing.
- Define genetic drift and explain its effect on the probability of survival of mutations.
- Recognize and give examples of the main classes of ecosystem and their structures.
- Give examples of ecological change that can drive evolutionary change.

***Sample* Content Expectations at Specific Stages (Points of Assessment)**

Fourth Grade

- Distinguish: solids, liquids, gases.
- Recognize sizes and scales: know measuring tools and techniques—rulers, balances, thermometers; make and interpret elementary bar and line graphs to display data.
- Be able to discuss motion and its causes: pushes and pulls (forces).
- Know how to observe and record operations of levers, pulleys, objects on inclined planes, spring-mass systems, and simple pendulums.
- Recognize that energy has several forms and that they can be inter-converted.
- Observe and describe some material transformations: e.g., phase changes, hydration, dehydration, solution, chemical reaction.
- Recognize such basic life processes as breathing, feeding, reproducing.
- Know the basic structure of higher plants; observe plant growth and its requirements.
- Recognize animal structures and behaviors and the groupings of animals and plants in communities.
- Observe and be able to describe similarities and differences between parents and offspring.
- Observe Earth, Sun, and Moon and discuss their motions and directly visible properties.
- Recognize rocks, soil, and fossils in rocks; land and water; mountains and plains, oceans and continents.
- Recognize some conditions and processes that cause weathering and erosion, stream formation, and sedimentation.

Eighth Grade

- Make measurements and perform calculations, paying attention to precision and accuracy.
- Make and interpret graphical displays of data.
- Understand and make simple calculations involving displacement, time, and average velocity.

- Define volume, weight, mass, density, and chemical and physical change.
- Demonstrate addition of forces in one dimension and explain the relation between net force and acceleration.
- Describe mechanical work as the effect of a force acting over a distance, and explain that the work done in lifting a mass or compressing a spring is stored as potential energy.
- Demonstrate basic familiarity with heat, light, sound, and electricity.
- Distinguish between, and give examples of, elements and chemical compounds.
- Describe directly observable properties of acids and bases and use of the pH scale.
- Describe accurately key differences between pro- and eukaryotic cells.
- Recognize photosynthesis as a primary energy-capture process of life, and the Sun as the indispensable source of that energy.
- Recognize and be able to express in simple taxonomic terms the vast range of plant and animal diversity.
- Identify structure/function relationships in physiological systems, e.g., reproductive, digestive, nervous, circulatory.
- Know the elements of Mendelian inheritance.
- Be aware of the history of Earth's biosphere and some of the basic evidence for its evolution.
- Understand that Earth is geologically active, with building and breakdown processes in continual operation.
- Know the rock cycle.
- Describe the solar system and know some relative orbit radii, periods, and planet and satellite sizes.
- Recognize the existence of myriad galaxies, their sizes, and intergalactic distances.

Common Grading Metric

As explained above, once NGSS was evaluated against the science content criteria, the standards were judged against a grading metric (shown below). As with state standards, NGSS could earn up to 7 points for "content and rigor," and up to 3 points for "clarity and specificity."

Content and Rigor

7: Standards meet all the following criteria:

- Standards are reasonably comprehensive in terms of content. Coverage for each of the three core scientific disciplines is adequate, and good decisions have been made about what topics to include under each heading.

- Not only is appropriate content covered by the standards, but it is covered in an articulate and readily understood way.

- Sound decisions have been made about what content can be left out. Excellent standards cannot cover everything in science, neither do they include superfluous or distracting material.

- The standards distinguish between more important and less important content and skills either directly (by stating which are more and less important) or via the number of standards and discussion devoted to particular topics. The standards do not overemphasize topics of small importance or underemphasize topics of great importance.

- The level of rigor is appropriate for targeted grade level(s). Students are expected to learn the content and skills in a rational order and at appropriately increasing levels of difficulty. The standards, taken as a whole, define science literacy for all students; at the same time, standards that run through twelfth grade are sufficiently challenging to ensure that students who do achieve proficiency by the final year will be ready for work or college.

- The standards do not overemphasize “life experiences” or “real world” problems. They do not embrace fads or display political-cultural biases. They do not imply that all interpretations of natural phenomena are equally valid. While these standards may not be uniformly perfect, any defects are marginal.

6: Standards fall short in *one* of the following ways:

- Some important content (as identified, for example, in our content criteria) is missing.

- Content is covered satisfactorily but the presentation is not of uniformly high quality.

- Some proposed content in the standards is unnecessary and distracting.

- Standards do not always differentiate between more and less important content (i.e., importance is neither articulated explicitly nor conveyed via the number of standards dedicated to a particular topic). In other words, these standards overemphasize a few topics of little importance or underemphasize a few topics of great importance.

- Some of the expectations at particular grade levels are set unrealistically high or too low.

- There are small problems or errors in the presentation of important subjects, such as those listed in content criteria.

5: Standards fall short in *at least two* of the following ways:

- Some important content (as identified, for example, in our content criteria) is missing.

• Content is covered satisfactorily but the presentation is not of uniformly high quality.

• Some proposed content in the standards is unnecessary and distracting.

• Standards do not always differentiate between more and less important content (i.e., importance is neither articulated explicitly nor conveyed via the number of standards dedicated to a particular topic). In other words, these standards overemphasize a few topics of little importance or underemphasize a few topics of great importance.

• Some of the expectations at particular grade levels are set unrealistically high or too low.

• There are a few problems or errors in the presentation of important subjects, such as those listed among our content criteria.

4: Standards fall short in *one or both* of the following ways:

• Although there are no grossly misleading or mistaken "standards," about half of the important content (as listed among our content criteria) is missing.

• There are errors or failures to set learning expectations high enough and appropriate to grade.

3: Standards fall short in *one or both* of the following ways:

• Although there are no grossly misleading or mistaken "standards," considerably more than half of the important content (as listed among our content criteria) is missing.

• There are frequent errors or failures to set learning expectations high enough and appropriate to grade.

2: Standards fall short in *one* of the following ways:

• Most but not necessarily all the important science content (as represented in our content criteria) is missing.

• Some of the content offered is superfluous or distracting, and even if not in error, it often fails to reach levels of sophistication that are grade-appropriate.

1: Standards fall short in *both* of the following ways:

• Most but not necessarily all the important science content (as represented in our content criteria) is missing.

- The content actually offered is frequently superfluous or distracting, poorly chosen, and even if not in error, it fails generally to reach levels of sophistication that are grade-appropriate.

0: Standards fall short in the following way:

- No effort has been made to represent the state and content of modern science, that is, the character and content of modern science are not recognizable in these standards.

Clarity and Specificity

3: Standards are clear, coherent, and well organized.
Both scope and sequencing of the material are apparent and reasonable. The standards provide practical guidance to users (students, parents, teachers, curriculum directors, test developers, textbook writers, etc.) on the science content knowledge and skills required. The level of detail is appropriate for expectations covering all K–12 science.

The document(s) is (are) written in prose that the general public can understand and is free of jargon. (Necessary technical terms and mathematical notation may appear: they are not jargon.) The standards describe measurable achievements—performance levels comparable across students and schools. The standards as a whole make clear the intellectual growth expected through the grades.

2: The standards are somewhat lacking in clarity, coherence, or organization.
Scope and sequencing of the material are not completely apparent or are not always useful for curriculum planning. The standards do not quite provide a complete guide for users as to the content knowledge and skills required. (That is, as a guide for users, these standards have shortcomings not addressed directly in the content and rigor review.) The standards provide insufficient detail. The prose is generally comprehensible but there is some jargon or vague language. Some of the standards do not imply measurable expectations.

1: The standards fail frequently to be clear, coherent, or well organized.
They offer only limited guidance to users (students, parents, teachers, curriculum directors, textbook writers, etc.) on the content knowledge and skills required, and there are shortcomings (regarding guidance for users) that are not addressed directly in the content and rigor review. The standards are seriously lacking in detail, and the language is sometimes too vague to make clear what is really being asked of students and teachers.

0: The standards are incoherent and/or disorganized.
They will not be helpful to users. They are sorely lacking in detail. Scope and sequence are a mystery.

Appendix B: About the Authors

Paul R. Gross (Lead Author)
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, Dr. 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).

Douglas Buttrey (Engineering)
Douglas J. Buttrey received a BS in biology from Wayne State University and an MS and PhD in chemistry from Purdue University. He held a SOHIO postdoctoral research fellowship in physical chemistry at Cambridge. After eighteen months as a visiting professor jointly in chemistry, physics, and materials science and engineering at Purdue, he joined the faculty in chemical engineering at the University of Delaware. He is currently the associate chairperson in chemical and biomolecular engineering at the University of Delaware and is a member of the university's Center for Catalytic Science and Technology. His research involves atomic-level design of complex materials for use in catalytic and alternative-energy applications. He has taught thermodynamics, materials science, and solid-state chemistry and statistics, and he has served as a visiting professor on five continents. Since 2008, he has worked actively with the Nelson Mandela Institution on a project to build high-level universities across sub-Saharan Africa and is committed to providing access to and education in science and technology to under-served populations. He recently won the Purdue University Chemistry Outstanding Alumni Award.

Ursula Goodenough (Biology)
Ursula Goodenough is a professor of biology at Washington University. She received her PhD in biology from Harvard University, and she previously served there as an NIH postdoctoral fellow and both an assistant and an associate professor. At Washington University, her lab utilizes the unicellular eukaryotic green soil alga, Chlamydomonas reinhardtii, to study both fundamental and potentially industry-applicable biological processes. Her long-term focus has centered on elucidating molecular-genetic features of

its sexual cycle, leading to the cloning and characterization of its mating-type locus and of genes involved in sex determination, mating interactions, the haploid-diploid transition in gene expression that follows gametic fusion, and the uniparental inheritance of chloroplast genomes. The lab's current focus is on the production of triacylglycerides by various unicellular algae as potential precursors for liquid transportation fuels. She teaches cell biology and molecular evolution and has written three editions of a widely used college textbook on genetics. She has served as president of the American Society for Cell Biology, among other positions of leadership in the organization, and she serves on national science committees, review panels, and editorial boards. She is a fellow of the American Academy of Arts and Sciences. She is the author of *The Sacred Depth of Nature* (Oxford University Press, 1998).

Noretta Koertge (Philosophy of Science)
Noretta Koertge is professor emeritus in the department of history and philosophy of science at Indiana University, where she continues to teach in the Hutton Honors College. After receiving a BS and an MS in chemistry from the University of Illinois in 1955 and 1956, respectively, she taught chemistry at Elmhurst College near Chicago and the American College for Girls in Istanbul. She received a PhD in the philosophy of science at the University of London (Chelsea College) in 1969. She then taught at the Ontario Institute for Studies in Education before coming to Indiana, where she served for a time as director of the Individualized Major program. She is former editor of the journal *Philosophy of Science* and edited *The New Dictionary of Scientific Biography*. She was elected a fellow of the American Association for the Advancement of Science in 1999 in recognition for her studies of the philosophy of Karl Popper.

Lawrence S. Lerner (Physics)
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 has consulted with many states on their science standards, frameworks, and other curriculum matters. He serves as associate editor of two scholarly journals.

William Schmidt (Math, Alignment to the Common Core State Standards for Mathematics)
William Schmidt is a university distinguished professor and co-director of the Education Policy Center at Michigan State University. He holds faculty appointments in measurement and quantitative methods and in the Department of Statistics. His current writing and research concerns issues of academic content in K–12 schooling, teacher

preparation, and the effects of curriculum on academic achievement. He is also concerned with educational policy related to mathematics, science, and testing in general. He is a member of the National Academy of Education and a fellow of the American Educational Research Association (AERA). Dr. Schmidt provided feedback and guidance on this review, and he will be coauthor of our forthcoming evaluation of Appendix L, which discusses the alignment between the NGSS and the Common Core math standards.

Martha Schwartz (Earth and Space Science)
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 BS 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 (Chemistry)
Richard Schwartz holds a BS 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 which 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 (Math, Alignment to the Common Core State Standards for Mathematics)
Dr. Wilson is professor of mathematics at the Johns Hopkins University, where he has chaired the Department of Mathematics. He received his PhD in mathematics from the Massachusetts Institute of Technology in 1972 and has published over sixty research papers in the field of algebraic topology. 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) and *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 provided feedback and guidance on this review, and he will be coauthor of our forthcoming evaluation of Appendix L, which discusses the alignment between the NGSS and the Common Core math standards.