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

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Math Feedback Provided by William Schmidt and W. Stephen Wilson

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Foreword

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

Nobody is satisfied with science education in the U.S. today. One need only look at TIMSS, PISA, and NAEP data to see what a mediocre job we're doing of imparting a solid science education to the average American student. Of course, there are multiple reasons for this failure, not least the poor preparation of too many teachers whose job it is to teach this critical subject.[1] But one key explanation is the shoddy quality of our academic expectations and standards themselves.

In science—perhaps even more than other subjects—states must honor their responsibility to set forth, explicitly and rigorously, the skills and content that schools are expected to impart and students are expected to learn at every grade level. Such standards need to be clear, meaty, challenging, well prioritized, and—perhaps most importantly—*teachable.* These are, after all, the expectations that should be used by practitioners to inform curriculum, textbook, and teacher preparation, that become the basis for state and local assessments, and that inform—or should inform—classroom-level planning and instruction. Done right, state K–12 science expectations set a firm foundation upon which the rest of science education across the state will be constructed. And particularly for teachers who may lack the content-specific expertise themselves, state standards will direct their planning, inform their instruction, and set a clear bar for student content mastery at each grade level.

Because getting this right is so vital, we at the Thomas B. Fordham Institute have been reviewing state science standards since 1998. In the most recent review, published just a year ago, our expert reviewers determined that the clarity, content, and rigor of most state K–12 science standards was mediocre to awful. And they assigned grades of C or worse to three quarters of the states. (Ten jurisdictions flunked altogether.)

Still and all, science education in America is hardly a wasteland. Our reviewers also awarded "honors" grades (B or better) to a quarter of the states for their K–12 science standards. Tens of thousands of our best and brightest high school students every year earn high marks on Advanced Placement exams in physics, chemistry, and biology. On the latest (2011) TIMSS science assessment, among fifty-six jurisdictions participating at the eighth-grade level, just twelve produced stronger results than the United States. Remarkably, three of those were U.S. states! (Massachusetts surpassed Taiwan, Minnesota rivaled Finland, and North Carolina was strong, too.) At the post-secondary level, the United States continues to house many of the world's premier institutions of scientific research, and our scientists continue to win an impressive share of Nobel prizes and other key awards in scientific fields.

So, 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

[1] Students of teachers who have degrees in math or science perform better than those who don't, yet most science and math teachers don't have degrees in the subjects they teach. "Building a Better Science Teacher," Pat Wingert, *Scientific American*, August 2012

possible to make it even *worse*. Particularly if in our effort to raise standards for all students, we systematically *lower* them for our best and brightest.

The Next Generation Science Standards project (NGSS)—a joint effort of the National Research Council, the National Science Teachers Association, the American Association for the Advancement of Science, and Achieve—indeed set out to overhaul the system in a hugely ambitious way. Their intent is nothing less that redefining science education for the primary and secondary grades.

To their credit, they've gone about this work in a commendably transparent way, making public (so far) two drafts of the proposed new standards as well as the National Research Council "framework" that is intended to furnish the intellectual/scientific underpinning for this redefinition of science education.

Our team previously reviewed the first draft—and team leader Paul R. Gross, an eminent biologist and former provost of the University of Virginia, reviewed the NRC framework. Those reviews found much that was promising but also a number of significant problems. As we reported in our commentary on the first draft, "the NGSS authors have much to do to ensure that the final draft is a true leap forward in science education." Among the key challenges uncovered by our reviewers as they scrutinized NGSS 1.0:

- [The authors] went overboard on "scientific practices," seemingly determined to include some version of such practices or processes in every standard, whether sensible (and actionable, teachable, assessable) or not. This led to distorted or unclear expectations for teachers and students and, often, to neglect of crucial scientific content…

- At the same time, paradoxically, the drafters left too much to curriculum developers by omitting (or leaving implicit) much crucial science content…

- The alignment between the NGSS draft and the Common Core math standards—something the authors have indicated is a priority—was weak. There are only infrequent and vague references to important mathematics content, which weakens some of the science standards (particularly in physical science in the upper grades) by omitting, for example, valuable lessons that require use of the relatively sophisticated math that the Common Core incorporates….

To what extent has NGSS draft 2.0 rectified these shortcomings, and are we significantly closer to a set of K–12 science standards that even states with strong standards of their own would do well to adopt?

In the pages that follow, we answer that question. For this analysis, we brought together a somewhat expanded review team, including a distinguished engineer and two acclaimed math specialists, as well as our veteran team of science experts, again led by Dr. Gross. (For more information about the reviewers, turn to page 8.) As they did for NGSS 1.0, and earlier for our most recent review of states' K–12 science standards, the team used a set of content-specific criteria to judge the quality, content, and rigor of NGSS 2.0 (see Appendix B).

Because forty-five jurisdictions have already adopted the Common Core State Standards for mathematics (CCSSM), and because of the close interplay of math and science, properly aligning the NGSS with those math standards is also critical. Toward that end, two experienced and highly regarded mathematicians—William Schmidt and W. Stephen Wilson—have reviewed NGSS 2.0 with an eye toward its treatment of critical math as well as the alignment between the evolving science standards and CCSSM. Their analysis is included in this review (see page 34) and provides detailed and specific feedback on what the NGSS authors must do to improve the alignment and to provide the context and guidance that practitioners need to intentionally link science and math in their planning and instruction.

Because NGSS 2.0 is still a draft, made public to collect feedback that will inform the final standards, we have not "graded" these standards. Instead, we provide both big-picture feedback and detailed, standard-specific commentary.

First, the good news: In a number of areas, the authors of NGSS 2.0 have made worthy improvements over version 1.0. For example,

- The alignment between the Common Core math standards and the NGSS has been strengthened. In addition to linking science standards to relevant math in the CCSSM within the main NGSS document itself, the authors have included Appendix K, which is devoted entirely to highlighting that alignment. For grades K–5, this document is thorough and provides clear, specific context and examples of how a teacher might align science planning and instruction with critical math content.

- Important engineering practices and content have been integrated into the discipline-specific standards, rather than isolated in a separate strand. Given that students need to learn critical content before they can apply it in engineering, subordinating engineering practices to science content is critically important.

- The authors are again to be commended for their honest, scientifically sound handling of evolution. While we offer some suggestions for further strengthening these standards, their inclusion is crucial.

- The first draft was presented in a confusing, difficult-to-navigate online platform. This draft was made available online and via PDF, thus making it more accessible and making it easier to track the progression of content across the grades.

- The authors made a serious effort, in an extended series of appendices, to justify their decisions and the resulting standards document. One need not agree with all their arguments (and we do not) to recognize the conscientiousness of these efforts to communicate with potential users of their work.

Unfortunately, large problems still abound in NGSS 2.0. Here are the most important of the major challenges that the drafters and revisers face as they move toward a final version:

- In an apparent effort to draft fewer and clearer standards to guide K–12 science curriculum and instruction, the drafters continue to omit quite a lot of essential content. The pages that follow supply many examples. Among the most egregious omissions are most of chemistry; thermodynamics; electrical circuits; physiology; minerals and rocks; the layered Earth; the essentials of biological chemistry and biochemical genetics; and at least the descriptive elements of developmental biology.

- As in version 1.0, some content that is never explicitly stated with regards to earlier grades seems to be taken for granted when referring to later grades—where, we fear, it won't actually be found if the earlier-grade teachers do not see it made explicit.

- Real science invariably blends content knowledge with core ideas, "crosscutting concepts," and various practices, activities, or applications. The NGSS erroneously claims that presenting science as such an amalgam is a major innovation ("conceptual shift"), which it isn't. Much more problematic, the NGSS has imposed so rigid a format on its new standards that the recommended "practices" *dominate* them, and basic science knowledge—which should be the ultimate goal of science education—becomes secondary. Such a forced approach also causes the language of these standards to become distractingly stereotyped and their interpretation a burden.

- As noted above (and praised), the drafters made a commendable effort to integrate "engineering practices" into the science rather than treating engineering as a separate discipline. Still—once again—their insistence on finding such practices in connection with so many standards sometimes leads to inappropriate or banal exercises—and blurs the real meaning of "engineering."

- The effort to insist on "assessment boundaries" in connection with every standard often leads to a "dumbing down" of what might actually be learned about a topic, seemingly in the interest of "one-size-fits-all" science that won't be too challenging for students. This is a mistake in at least two ways. First, it potentially limits how far and how deep advanced students (and their teachers) might go. (The vague assertion that this can be dealt with via "advanced" high school courses helps almost not at all.) Second, it usurps the prerogative of curriculum builders and those constructing (and determining proficiency levels on) assessments to make these decisions for themselves. It's one thing to set forth what *must* be covered in school; it's quite another to try to put limits on how much more *might* be covered—and to suggest that *not* going farther is perfectly okay, even for pupils who could and would. What's more, these "boundaries" are often used to strip science of critical mathematics content.

- A number of key terms (e.g., "model" and "design") are ill defined or inconsistently used.

- Even as the amplitude of new appendices adds welcome explanation and clarification of what is and isn't present and why, it also produces a structure for NGSS that most users, especially classroom teachers, will find complex and unwieldy. Even the attempts to help users understand and apply these standards (as in the four-page PDF document titled "How to read the NGSS standards") are complicated and confusing. Moreover, the various appendices are clearly aimed at different audiences without ever saying so. Will a fifth-grade teacher actually make her way to Appendix K to obtain additional (and valuable) information about science-math alignment and some pedagogically useful examples? Will the final version of NGSS omit some of the intervening appendices that have more to do with the philosophical, political, and epistemological leanings of the project and its leaders than with anything of immediate value to real schools?

- Although the "alignment" of NGSS math with Common Core math is improved, there also seems to have been a conscious effort by NGSS drafters not to expect much science to be taught or learned of the sort that depends on math to be done properly. This weakens the science and leads, once again, to a worrisome dumbing down, particularly in high school physics—which, as the reviewers note, "is inherently mathematical." It must also be noted that Appendix K, valuable as it is in grades K–5, is essentially AWOL from the middle and high school grades, where it is most needed. Indeed, our math reviewers found "no guidance about the specific mathematics to be used for individual science standards at the high school level. And only occasional guidance at the middle school level."

Conclusion

As in reviewing draft 1.0, our goal here is to provide feedback to NGSS drafters and overseers that may help them solve problems that the present draft presents. But let us speak the truth: Though we did not review NGSS 2.0 with an eye toward "grading" it, it's clear to the review team that if draft 2.0 were to become the final version of NGSS, only states with exceptionally weak science standards of their own would likely benefit from replacing them with these "next-generation" standards.

We sincerely hope that this situation can be significantly altered and improved by the NGSS team between now and the issuance of their final version a few months hence. Indeed, we urge them to take as much time as is necessary to make this come out well. The present draft is problematic in more ways than it is strong.

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Commentary and Feedback on Draft II of the Next Generation Science Standards

Science Feedback provided by Paul R. Gross with Douglas Buttrey, Ursula Goodenough, Noretta Koertge, Lawrence S. Lerner, Martha Schwartz, and Richard Schwartz

This is our third response to the present multi-state initiative in science education for K–12. We reviewed the National Research Council's Framework for what was to become these Next Generation Science Standards (NGSS) and the first draft of those standards. In both documents, we found merit, some energetic proposals for change, and extensive discussion of the reasons for them. We also found some disquieting features among the proposals and did our best to specify and justify the concerns. Our praises, like those of other commentators, were obviously noticed. That has not been the case for a number of our main concerns. We hope that they will receive a more constructive response this time around. It is no exaggeration to say that hope for real improvement of K–12 science in this country is at stake, beginning with this first concrete step: preparing the best possible standards and realizing what must follow in curriculum and classroom if the standards are actually to make a difference in how much and how well children learn science.

Our appraisal of the first NGSS draft found that the document's "unswerving fealty to the NRC Framework" had two drawbacks:

a) An expansionist conception of appropriate pedagogy for K–12 science education

b) Omission and overgeneralization of scientific content, owing to the drafters' determination to wind up with fewer standards than have previously been found in strong sets of standards

In other words, the drafters sought simultaneously to expand and to compress (at least the knowledge base of) K–12 science education.

In general, these two broad concerns have not been addressed. And so we will express them once again.

I. Organization of the Standards

The proposed standards are presented two ways in the present draft: by "topic" and by "Disciplinary Core Idea" (DCI).

When organized by topic, the standards are presented by grade level and then divided into one of the four science disciplines (Physical Science; Life Science; Earth and Space Science; and what is termed Engineering, Technology, and Applied Science). Within each discipline, performance expectations are grouped by “topics,” such as “energy,” “waves,” “earth’s surface systems,” and on.

When presented by DCI, performance expectations are organized similarly, except that they are grouped into Disciplinary Core Ideas (i.e., “Matter and Its Interactions,” “Motion and Stability: Forces and Interactions,” etc.) rather than by topic.

At each grade level and for each topic or DCI, a series of performance expectations is presented. Each performance expectation includes a “clarification statement” and an “assessment boundary” that specify how student mastery will be assessed. Take, for example, the following middle school physical-science performance expectation:

> **MS-PS2-b. Design an investigation to produce empirical evidence supporting the claim that the change in the motion of an object depends on the sum of the forces on the object and the mass of the object.** [Clarification Statement: This performance expectation addresses both balanced (e.g. Newton’s First Law) and unbalanced forces. Both frame of reference and appropriate choice of units should be specified.] [Assessment Boundary: Forces and change in motion are limited to one-dimension. The use of trigonometry is not an expectation. F=ma is not directly assessed. Only experiments in which one variable is changed are to be assessed. Assessments of measurements of the change in the motion are qualitative.]

Beneath the three to six related performance expectations, the standards link to “Science and Engineering Practices,” “Disciplinary Core Ideas,” and “Crosscutting Concepts” that were drawn from the NRC Framework and used to develop the performance expectations.

Finally, the authors provide a “connections” box that, in the current draft, links to related Common Core ELA and math standards. (The final NGSS, as promised, will include connections to other DCIs within and across grade levels.)

In addition to the standards themselves, the authors have provided eleven appendices, a glossary of terms, a document with “front matter” (introduction, foreword, etc.), a document explaining why standards matter, information about public attitudes towards science standards, and a video designed to help lay readers read the standards and related material.

Even the most sophisticated reader of publications such as this must find it all very heavy going.

II. Background and Introduction

Conceptual Shifts

The first of eleven appendices (Appendix A) to the new NGSS document deals with “conceptual shifts” introduced by its enabling predecessor, the (NRC) Framework for K–12 Science Education.[1] Those new concepts take shape in the second-draft “Next Generation” science standards (NGSS). First among the declared innovations is this decision: K–12 Science Education will proceed at all grade levels via a continuous, consistent "intertwining" of one "dimension"—basic scientific knowledge from the main sub-disciplines (formerly "content," now "Disciplinary Core Ideas" or DCI)—with two other, equally weighted dimensions: "Science and Engineering Practice" and "Crosscutting Concepts." Another *Framework* novelty was the decision that a new, fourth discipline, "Engineering, Technology, and Applied Science," would be added to the core subjects of K–12 science, thus joining the traditional Physical, Biological, and Earth/Space sciences. In fact, however, the NGSS now provide most of the authorized Engineering emphasis within the "Practices" dimension rather than as an independent content (knowledge) discipline —a sensible change from the original proposals of the Framework.

There is, however, less "conceptual" change than is claimed in simply taking careful note of the practices (effectively, the *doing*) of science, alongside basic knowledge of content, nor in identifying some of its "Crosscutting Concepts." Most of the relevant practices of science have for some time been incorporated into, for example, the standards of many states, under such prevalent heads as "hands on science," "Inquiry learning,"[2] and "Scientific Reasoning."[3] And a thorough unpacking and elaboration of "Practices" in the current NGSS Appendices makes clear that the same skills and strategies formerly invoked under "Inquiry" and "Scientific Reasoning" are now to be acquired as Practices and demonstrated in student performance. The real difference is in the elaborating texts.

Nor is there a big "shift" actually to be found in what are here called Crosscutting Concepts, which were recognized and emphasized even in nineteenth-century philosophy of science—as in, for example, "consilience," a distinguishing feature of good science adduced by the polymath William Whewell (1794–1866). In our own time (for another example), a now-classic work of epistemology by philosopher of science Susan Haack modeled the character and growth of scientific knowledge on the solutions of a vast crossword puzzle, with the interlocked supports and dependencies of "across" with "down," the clues and answers that fit, confirming the validity of earlier fill-ins.[4] In state science standards, crosscutting concepts have been a regular and important emphasis for decades. Those documents usually identify them as "Themes" or "Big Ideas" to be worked into the narratives and content-sequences of what in the NGSS are called the Disciplinary Core Ideas. So far, then, the conceptual shifts are slight: Only their theoretical language has been expanded.

Novelty

What *was* new in the NRC Framework, however, and is conspicuously new in the NGSS, is an insistent, consistent, and *forced* intertwining of the three "dimensions" identified above—in every standard, without exception—whether or not it makes sense for the particular content supposed to be addressed by that standard. This is indeed a conceptual shift. It will also (if implemented) lead to a shift in the way curricula are built and, especially, in the way assessments of student performance are designed. Indeed, if the intentions of the NGSS are followed at the classroom level, existing assessment practices will need much modification. In the discussions of the standards by DCI below, it will be clear that this forcing of the Practices dimension into every standard often makes the performance expectations (which is what standards are) eerily remote from the content that the standard presumably addresses. Many examples of this are provided below.

Standards: "Not a Curriculum?"

The second major point made in Appendix A is this strong assertion: "The Next Generation Science standards are student performance expectations—Not curriculum." Indeed, they are not a curriculum. But then, *no* extant framework or set of standards for K–12 science is itself a curriculum. Curricula are built upon standards; the standards define their shape, substance, and limits. But curricula are the realization of standards, just as standards are the realization of frameworks. Now, Appendix A insists that the NGSS organization does not limit instruction or curriculum. To wit,

> It is essential to understand that the emphasis placed on a particular Science and Engineering Practice or Crosscutting Concept in a performance expectation is not intended to limit instruction, but to make clear the intent of the assessments.[5]

This confident assertion is contradicted, however, by the innovation of "Assessment Boundaries" that now accompany the NGSS standards. These *limit*, precisely, what is to be assessed, presumably in aid of controlled grade-wise progression in sophistication and depth. In fact, however, they place explicit limits on performance expectations (and the implied sophistication and depth) of the standards. Many examples are identified below and in the appendix. What doesn't get into the standards, or is explicitly disavowed or proscribed for assessments, is unlikely to get serious attention in the curriculum or the classroom. Lesson planners and already burdened teachers are unlikely to occupy themselves assiduously with material that will never be tested.

Thus while the standards are not a curriculum, the shape of curricula that might emerge if these NGSS are adopted and applied rigorously to curriculum building does begin to take shape. It would be a curriculum, with assessments derived from it, in which scientific content knowledge is but one component of the performances expected from students, a component *and not necessarily the major one*. (Many examples below.) Emphasis is very frequently placed upon other performances. The specified achievements in these standards are the required "performances," and *those* tend to be demonstrations of capability in the various practices—written and spoken communication, model-building, explanation, data gathering, "analysis." Quite a few of them are identified in the documentation as particularly pertinent to or important for engineering and applied science. In this sense, the NGSS *are* a conceptual shift: *These standards are primarily a vision of altered pedagogy for K–12 science*, secondarily about acquiring and understanding a reduced but ostensibly more sophisticated ("deeper") sample of basic science content knowledge.

To put it as simply as possible: If there is to be major emphasis on certain *behaviors* (associated, be it noted, not just with science, but with all technical and academic discourse) and repeated restrictions are placed on advanced or even slightly difficult scientific content (such as mathematics and calculations), then the potential acquisition of content knowledge, at least by some students, is also limited—in fact, reduced.

Because we found remarkable commonality among the concerns expressed across this group of reviewers, regardless of individual specialty, they will be addressed in general and with comments on the actual standards for the traditional Disciplinary Cores. A number of individual standard-specific comments are placed in an appendix, separating them from more general comments in each discipline. The reader should be aware that each reviewer is or has been a teacher of science as well as a professional scientist in at least one Disciplinary Core, and that experiences of all grade levels, primary through graduate school, are represented within this group.

III. Discipline-Specific Feedback

Physical Science

Physical science is reasonably well handled in grades K–5, where performance expectations lay a foundation on the basis of which students can build an intuitive grasp of the subject matter. Issues raised at these levels (articulated in detail in Appendix A) are mostly specific and easily remedied. For example, "Motion and Stability: Forces and Interactions" is first seen at grade 2. What is presented is appropriate, but since forces and interactions underlie pretty much all of physical science, it might be a good idea to introduce some simple experiences at the Kindergarten and first-grade levels, as well.

Unfortunately, at the middle school level, and even more at the high school level, the document fails in many ways:

1. In spite of much discourse on the importance of mathematics, quantitative work is dodged and avoided throughout, often via specific Assessment Boundaries. This is especially damaging in high school physics, which is inherently mathematical. But such modestly mathematical exercises as balancing chemical equations are absent as well. (There seems to be no hint anywhere of a chemical equation or formula.)

2. Circumlocution is often used, bewilderingly, where straightforward terminology exists and is convenient. HS-PS2-a exemplifies the lengths to which this document goes to avoid a simple, transparent statement such as $F = ma$.

3. Dynamics, the foundation of virtually everything else in physics, is slighted at the high school level. Kepler's laws are mentioned just once, in an Assessment Boundary (HS-ESSE-e). Needless to say, there is nothing quantitative about kinematics, which is a prerequisite to a high school–level understanding of dynamics.

4. Great swathes of basic physics are missing entirely. Most notable, perhaps, is thermodynamics. There is nothing about heat engines, the laws of thermodynamics, or

much of anything at all beyond a fleeting mention of heat capacity (and that mention fails to use those words!). Latent heat is hinted at, but never actually touched, in a passage about mixing ice and water. (Appendix B contains more specific detail about important content that is merely assumed or missing entirely.)

5. Although the word electromagnetism (with variants) is often used, there is no real attempt to present the subject in a systematic way. Coulomb's law is mentioned (but never quoted); Ampère's law is never mentioned by name; there is nothing about Faraday's law, let alone the complementarity of Ampère's and Faraday's laws, other than a passing mention that is never nailed down. And at the K–5 and middle school levels, there is nothing about building and experimenting with electric circuits, let alone any mention of such practical pillars as Ohm's law or the distinction between direct and alternating currents.

6. The treatment of energy is poor. Even loose definitions are too long delayed and, when presented, they are backward. Students are expected to work with the concept of energy minus any real understanding of what they are working with. The work-energy theorem, which is the foundation stone of a genuine understanding of the meaning of energy in its most elementary form, is absent. Indeed, the word "work" and its definition, $W = Fx$, are nowhere to be found. There is much loose talk about the conversion of macroscopic energy into heat energy (though the wording makes things obscure), but straightforward exposition is lacking.

7. There is an entire section on waves, and it begins well at the primary grade levels. But there is no treatment of harmonic oscillation or much at all about mechanical oscillators, which are the sources of mechanical waves.

8. The varieties of chemical bonds are nowhere to be found, though the student seems to be expected to know something about the biochemical basis of life. How this is to be done when neither stoichiometric nor structural chemical formulas are touched on is a mystery.

9. Acids, bases, molarity, chemical reaction rates and equilibria, solutions, important commercial chemical processes—there is almost nothing about these subjects. There is some mention of energy levels, but nowhere is there any explanation of what they are or how they arise. The Bohr atom does not exist here. Quanta and Relativity seem to be off limits.

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

11. Some basic astrophysical concepts are presented—the Big Bang (and even a passing mention of the cosmic microwave background), a bit about stellar evolution, galaxies—but there is no mention of such great current questions as dark matter or dark energy.

Physical Science—Additional Comments for Chemistry

Using the assertion that it is not a curriculum, the NGSS authors omit most of the chemistry content traditionally found in K–12 classrooms. Missing are topics like gas-law relationships, the chemistry of carbon and its compounds, the mole concept, empirical and molecular formulas, solution preparation, concentration, and dilution, and acid/base neutralization reactions and the pH scale, to mention just a few. When topics are included, they often are somewhat advanced, like bond energy or chemical equilibrium. However, their inclusion is problematic because of insufficient background preparation in lower grade standards, use of low-level vocabulary, or content limits specified in the Assessment Boundaries. And unfortunately, if a topic is not required by the NGSS, it is not likely to be taught.

The assumption is that by limiting the breadth of topics, the specifically required content in the NGSS will be thoroughly mastered by all students. Appendix B states,

> "One of the important components to the vision of the *Framework* and the NGSS is the focus on a smaller set of core ideas that build over time. With the practical constraints of class time availability and the commitment to remain within the scope of the NRC *Framework*, the NGSS writers were not able to add new core ideas to the standards."

This time constraint (and the writers' devotion to the Framework) is used to explain why so many topics were not included in the NGSS. There is no mention that the pervasive hands-on-learning and assessments by demonstration, mandated as "Practices," must consume quite a lot of instructional time that might otherwise be devoted to essential content.

Despite claims that the standards have content depth and numerous connections to other ideas, they are quite shallow and exclude important ideas that are normally taught. Conservation of mass (or matter or atoms) is an example of a frequently (but shallowly) presented topic. Balancing chemical equations is a basic illustration of this conservation law. Regrettably, this universal activity is not part of the NGSS.

The importance of mathematics is stressed, but there is almost no problem solving in the NGSS. Stoichiometry, balancing chemical equations, and finding molecular mass (weight) from atomic masses are all outside the assessment boundaries. Percent composition and molarity are omitted math topics. While not specifically connected to math, chemical formulas (both naming and writing) of ionic and molecular compounds are also not addressed in the NGSS.

This quote from Appendix B does not justify the exclusion of stoichiometry:

> "In some cases, like stoichiometry, the conceptual understanding for why chemists do stoichiometry was already in the standards. The teams wanted to make the mathematical practice more explicit through the clarification statements, but not have a separate performance expectation requiring that all students do gram to gram calculations."

On the first page of Appendix K is the following statement relating to math and science learning:

> "Science is a quantitative discipline, which means it is important for educators to ensure that students' learning in science coheres well with their learning in mathematics. To achieve this alignment, the NGSS development team worked with the CCSSM writing team to ensure the NGSS do not outpace or otherwise misalign to the grade-by-grade standards in the CCSSM. Every effort has been made to ensure consistency. It is essential that the NGSS always be interpreted, and implemented, in such a way that they do not outpace or misalign to the grade-by-grade standards in the CCSSM (this includes the development of NGSS-aligned instructional materials and assessments)."

The writers are properly concerned that the mathematics in the NGSS not be more advanced than the corresponding CCSSM. (See our separate discussion of the alignment between the two.) They need not worry, since quantitative/mathematical problems are practically non-existent. It is hard to imagine how the writers can envision science as a quantitative discipline, yet specifically omit gram-to-gram conversions in chemistry.

Most of the Clarification Statements added to each standard include Assessment Boundary instructions. These instructions weaken the academic level by specifically excluding basic concepts. For example, "mole" appears in a clarification statement for HS PS1-h as a "conversion from the atomic to the macroscopic scale." Unfortunately "mole" is never defined, and this brief quote is the only reference to moles in the entire document. Atomic mass is also excluded in the assessment boundary of MS PS1-d, yet without atomic and/or molecular mass, moles cannot be connected to the mass of a pure substance or the number of atoms or molecules in a sample.

Numerous concepts that will be developed more thoroughly in high school should first be introduced in middle school. "Ion," for example, is used in HS PS1-c without explanation, but the testing of "polyatomic ions" was excluded. Then why is the polyatomic "ammonium" ion used in "ammonium chloride" as a recommended reactant in MS PS1-g?

"Polarity" is listed as just one of a number of properties of pure substances (HS PS1-b). It is not defined, nor is the connection made between polarity and molecular shape. According to a computer search, the *polarity of molecules* and the chemical bonds within and between molecules are not found, nor are electronegativity, Lewis dot structures, and sizes of atoms and their ions. Ionization energy is specifically "not required" (HS PS1-b). Concepts needed to support high school–level standards *frequently avoid using appropriate vocabulary* and/or lack sufficient background development in earlier grades. This weakens the high school program and results in students who are ill prepared for university-level courses in physics, chemistry, and engineering. Example: Solids and liquids are marginally introduced in early elementary grades, but the topic of gases is postponed.

Another example of weak preparation from page 1 of DCI PS.4.B:

> Some materials allow light to pass through them, others allow only some light through and others block all the light and create a dark shadow on any surface beyond them (i.e., on the other side from the light source), where the light cannot reach. (1-PS4-d)

Here is a typical missed opportunity to use the appropriate vocabulary: transparent, translucent, opaque.

A third example: To be prepared for high school chemistry, middle school students should learn about molecules and ionic, covalent, and metallic chemical bonds. Yet these basic bond types are not found in the NGSS for middle school. Which may be why they are (inexcusably) missing in the high school standards!

The term "interaction" is used in place of the universally employed "bond." This is replacing a one-syllable word by a four-syllable word that doesn't convey as much. The weaker "intermolecular forces" (bonds) between polar molecules, like dipole-dipole bonds, are specifically excluded. Also not mentioned by the NGSS are the London Dispersion forces and van der Waals forces that allow non-polar gaseous molecules to condense into liquids and then into solids.

The important and unique characteristics of water are omitted in this edition of NGSS. These include the strong covalent bonds between the hydrogen and oxygen atoms within a molecule, the angular shape of the water molecule and its polarity, and the weak but nonetheless important hydrogen bonds, which attract water molecules to their neighbors. Also missing is discussion of the critical thermal properties of water: latent heats of fusion and vaporization, and the high value of specific heat.

It is disappointing that in this document, where "model" is used hundreds of times, important models of the atom are essentially ignored. The Bohr model is neither named nor described and the Quantum model is only mentioned as it relates to the dual nature of light (HS PS4-e).

Missing also are orbitals, electron transitions/emission spectra, and the beautiful way the Quantum Theory "explains" the arrangement of elements on the periodic table.

Consider just one of the two Periodic Table standards:

> **HS PS1-b: Use the periodic table as a model to predict the relative properties of elements based on the patterns of electrons in the outer energy level of atoms.** [Clarification Statement: An example of a pattern that predicts element properties would be Group I of the periodic table. These elements all have one electron in the outermost energy level and as such, are all highly reactive metals. Other properties could include types of bonds formed with other elements, number of bonds formed, and reactions with oxygen.] [Assessment Boundary: Only for main group elements (not transition metals). Ionization energy is not required.]

There is no previous background to support this standard. What is an energy level? Why in Group 1 does one outer electron make the element a metal? What is a metal, anyway, or a non-metal, or a semi metal? Hydrogen appears to be in Group 1. Does that make it a “highly reactive metal”? What kinds of bonds and how many bonds do Group 1 reactive metals form? Why does the A.B. exclude transition elements such as iron, copper, and silver? What is Ionization Energy and why was this useful periodic property excluded?

Finally, a word about safety: At least two standards ask students to deal with potentially dangerous properties and related activities. In MS PS1-e, boiling point and flammability are suggested as properties of reactants and products worthy of study. And in 5 MS PS1-d, students are required to

> “Design and conduct investigations on the *mixing of two or more different substances* to determine whether a new substance with new properties is formed.”

This standard seems to be encouraging students to just mix stuff together and see what happens. Dangerous!

Life Science

The Structure and Language Issues

As in the other core disciplines, there is much missing content in these Life Science standards. Oddly, on the other hand, several of them illustrate well another, almost contrary difficulty: hyper-compression—that is, cramming into a single standard vast quantities of content, such that what is really represented is an entire chapter or unit of study in the discipline, rather than a discrete performance expectation. But these two problems are common to many of the standards, and their character will emerge clearly in standard-specific comments for all the disciplines, as we proceed.

In the life sciences, meanwhile, and as elsewhere in NGSS, the central problem resides in the language employed, and it follows from the standards’ preoccupation with “Practices,” which follows from the Framework’s proposal for the design of standards. Ruthless compliance with that proposal forces every standard to focus upon performance expectations that are *behaviors (or activities) as opposed to demonstrations of knowledge.* Behaviors and activities are legitimate performance expectations; but when *all* the expectations take that form, a system of standards, which is in principle about knowledge as well as skills, becomes ostentatiously one-sided. The resulting standards statements may not relate in a compelling way to the knowledge that is supposed to be the directing content dimension.

The following are extended comments on just a few selected standards, discussed at sufficient length to illustrate this general problem: vague, un-interpretable, un-assessable performance expectations couched in behavior terms. This can be best understood via examples.

Elementary School Level:

> **K-LS1-a. Collect, analyze, and use data to describe patterns of what plants and animals (including humans) need to survive.** [Clarification Statement: Data can come from direct observations and other sources. An example of a pattern is that plants need sunlight and water and animals need food and water. Scientists look for patterns when making observations.] [Assessment Boundary: Survival needs should be limited to food for animals and water and light for plants.]

If this is a literal performance expectation, then the student will need actively to *collect data*, and then use them to *describe patterns* in speech (in Kindergarten!). The Clarification shows what "pattern" means here: a *conclusion* about the needs of plants and animals for food, water, and sunlight, in two different combinations. Even aside that fatal ambiguity of the term "pattern," the relative contributions of pupil and teacher are completely obscure. Who will *collect* and *analyze* data? And whence? In the field, the animal house, in books, on the Internet? And with how much guidance? Reading this standard seriously, one has no way of deciding who—pupil or teacher—will actually do what, much less how to assess the "performance" of each pupil. The standard, as written, offers a perfectly good general idea of useful science-learning activity for Kindergarten. Its language taken literally, however, completely obscures the good general idea in a fog of *collecting*, *analyzing*, and *using* "data." In Kindergarten. This is a fine, early example of the inexorable "intertwining" discussed elsewhere in our review.

Middle School Level:

> **MS-LS1-d. Design and conduct an investigation to gather evidence to support explanations that the body is a system of interacting subsystems composed of groups of cells working to form tissues and organs specialized for particular body functions, and that scientific advances in understanding of those systems have led to improvements in nutrition, health, and medicine.*** [Clarification Statement: Emphasis is on the interaction of subsystems within a system (i.e., circulatory, excretory, digestive, respiratory, nervous).] [Assessment Boundary: The assessment should provide evidence of students' abilities to identify evidence supporting explanations for the interactions of body systems, and the normal and abnormal functioning of those systems. Assessment should not focus on the mechanism of each body system.]

This standard is not really about knowledge of physiology or the physiological systems of a body. It is about *designing and conducting an investigation*. What kind of investigation? A gathering of evidence. Where? Well, presumably from the teacher, or books, or online. So the assessment is, as indicated, to be concerned not with the physiological systems and subsystems but with the *identification of evidence that* *supports certain explanations* of them. Where do the explanations come from? The teacher? Independent searching by the student? *Assessing knowledge of the systems themselves, and their workings, is proscribed*. So the performance expectation is that of recognizing assertions about what some physiological systems do (but not how they do it) and about how they connect with other such systems. Hidden in the aforementioned "abnormal" functioning is additional knowledge—of physiological systems in malfunction. That is a bit of pathology, too! And all of that is indicated (by the asterisk) to be a part of (the intertwining of) engineering and applied science (more practices). Whole units of instruction lie buried in this innocuous-looking standard, and it is impossible to guess what is to be assessed in practice—or to be learned.

> **MS-LS3-b. Apply scientific knowledge to support the explanation that changes (mutations) to genes located on chromosomes affect proteins and may result in harmful, beneficial, or neutral effects to the structure and function of the organism.** [Clarification Statement: Emphasis is on constructing explanations that genetic mutations can result in harmful, beneficial, or neutral effects to the structure and function of an organism.] [Assessment Boundary: The assessment should provide evidence of students' abilities to communicate the relationship between genetic mutations and variations within a population. The assessment should not require students to describe the changes at the molecular level or any mechanism for protein synthesis.]

What scientific knowledge is to be applied to "support the explanation" that gene mutations affect proteins and may be harmful, beneficial, or neutral with respect to the organism's structure and function? *Molecular-level phenomena and structural chemistry are proscribed*. The student is asked to support (with scientific knowledge) an "explanation" that, first of all, is not an explanation. It is an *assertion*. Gene mutations can change proteins, and these changes can be positive, negative, or neutral for the organism. If there is to be no biochemistry, "scientific knowledge" of protein changes that are functionally neutral is going to be very hard to find! If no objective marker for the putative neutral mutation (DNA sequence change, amino acid change in a protein) can be invoked, how is the key assertion ("explanation") to be "supported?" The standard drowns in its own "practices" language.

High School Level:

> **HS-LS1-b. Critically read scientific literature and produce scientific writing and/or oral presentations that communicate how DNA sequences determine the structure and function of proteins, which carry out most of the work of the cell.** [Clarification Statement: Emphasis is on the conceptual understanding that DNA sequences determine the amino acid sequence; thus, protein structure and function.] [Assessment Boundary: The assessment should provide evidence of students' abilities to read critically and identify key ideas and major conceptual ideas of the relationship between structure and the

processes that lead to protein synthesis. The specific steps of transcription and translation or actual protein structure are not assessed.]

The performance expectation has to do, first, with critical reading and then either with writing or making a speech about how DNA sequences determine the structure and function of proteins. This represents a large unit in a real, probably AP-level biochemistry course or at least in a sound chemistry course, including work on nucleic acids and proteins, their structural formulae, and their main functions—*for which no prior evidence appears in the standards for earlier grades*. But now the Assessment Boundary rules out engagement with transcription or translation (i.e., the synthesis of a protein based on information originally in DNA) and the actual structure of a protein (i.e., the relationship between the amino acids of a polypeptide and the resultant macromolecule). So the teacher will be assessing reading comprehension in some piece of scientific literature, and then some writing or some talk about it, without much fussing about the chemical or biological essentials of nucleic acids and proteins. Or, as one hopes is more likely, the teacher will ignore the first and main statement of this "standard' and simply determine how much the student *knows* about the pathway from nucleotide sequence in DNA to a functioning enzyme or structural protein. Again, the "intertwining" imperative leaves all the key detail of curriculum, lesson plan, laboratory, and assessment to others. What looks like a compact but deep standard is, in fact, a loose summary of a large and detailed unit of study in cell biology/ biochemistry.

HS-LS4-a. Produce scientific writing that communicates how multiple lines of evidence, such as similarities in DNA sequences, anatomical structures, and order of appearance of structures in embryological development, contribute to the strength of science theories related to natural selection and biological evolution. [Clarification Statement: Emphasis is on identifying historically reliable sources of scientific evidence contributing to the strength of the theories of natural selection and biological evolution (e.g., DNA sequencing, embryology, anatomy) and evaluating how multiple lines of evidence contribute to an understanding of evolution.] [Assessment Boundary: The assessment should provide evidence of students' abilities to evaluate the strength of the evidence.]

This "standard" alone incorporates most of what would appear in a serious (minimal) list of "must-have" sub-topics for all of evolutionary biology at the high school level. What causes it to differ from such a *set* of standards on evolution is that, as written, *this Performance Expectation is about writing*, not about knowledge. The performance it requires has two parts: (1) writing well enough to communicate what is generally covered in the relevant unit or chapter of a good biology textbook and (2) the ability to distinguish "historically reliable" sources from their opposites. And the teacher/assessor must be able to recognize that ability—reliably. A splendidly tall order, so long as there is not much else going on in that semester of high school biology.

> **HS-LS2-f. Ask questions to define a problem caused by changes in population, resources, and/or the environment that can be solved through environmental engineering of solutions specific to the competition of organisms for matter and energy.*** [Clarification Statement: Emphasis is on students understanding that competition between organisms is for matter and energy to survive, grow, and reproduce.] [Assessment Boundary: The assessment should provide evidence of students' abilities to identify questions that define the problems when conditions (e.g., invasive species, predator removal, extreme weather, land use) are altered. The questions should be scientific in nature and useful in defining a problem that has an environmental engineering solution.]

The body of knowledge underlying this "standard" is important. But the relationship to it of the performance expectation here specified is at least ambiguous, if not incomprehensible. Interspecific and inter-organismal competition for resources in an ecosystem is easily demonstrable; success and failure in such ongoing competition can depend upon chance or accidental changes in the elements of the system. But the performance expectation is about none of these! Rather, it is about *"asking questions to define a problem"* associated with one of those changes. The requirement would appear to be either trivial or impossible to fulfill, depending upon what the eventual assessor has in mind.

> **HS-LS1-g. Develop and revise a model to support explanations about the role of cellular division and differentiation in producing and maintaining complex organisms composed of systems of tissues and organs that work together to meet the needs of the entire organism.** [Clarification Statement: Emphasis is on the concept that genetically identical cells produced from a single cell during embryological development differentiate and become tissues that make up organs within organ systems working together to meet the needs of the organism.] [Assessment Boundary: The assessment should provide evidence of students' abilities to show strengths and/or limitations of a model to demonstrate the development of differentiated cells with specific functions necessary for the organism to survive. Assessments could use a computer simulation. Emphasis is not on recalling the steps of mitosis or specific gene control mechanisms.]

Here, the student is asked, first, to have acquired a good grasp of at least the generalizations of developmental genetics and biochemistry, i.e., the course and mechanisms of cell differentiation and the morphogenesis that follows in multicellular organisms. But this is just a background, the *sine qua non*. The student is *then* required to "develop and revise a *model*" of the basic process that supports the core knowledge of – precisely– the developmental genetics and biochemistry content! Yet, in all this, neither the steps of "cellular division"— mitosis (why not?) nor "specific gene control mechanisms" (much more serious!) are to be invoked. On the other hand, a computer simulation is a possible performance, even though knowledge of the elementary steps of that which is to be simulated is not required (assessed). It is possible that this "standard" actually means or wants something; but this developmental biologist is not sure about what it might be.

The NGSS and its Treatment of Evolution

Elementary School Level:
While the writers are to be commended for using the term "common ancestry," which is perhaps the most important concept in evolution, they fall short in conveying its centrality and meaning. In LS4.A, we read, "Some kinds of plants and animals that once lived on Earth (e.g., dinosaurs) are no longer found anywhere, although others now living (e.g., lizards) resemble them in some ways." To emphasize common ancestry, this would be better phrased as, "resemble them in many ways." This is much improved-upon in MS-LS4-a, so a tune-up in the elementary category should be easy to make.

Middle School Level:
The writers are enthusiastically applauded for giving as much emphasis as they do to evolution in middle school. The majority of existing state standards make either no mention of the topic at all or some vague statement about change over time, meaning that a student who takes no high school biology has no engagement with this subject.

High School Level:
At this point, the concept of common ancestry should be given center stage, developing the material from middle school. Particularly given the paltry attention given to this concept in almost all existing state standards, the NGSS should be offering leadership here, recommending that students make models and read literature about evolutionary history, trees showing the various eukaryotic radiations, the timelines, something about organelles coming in as endosymbionts, about how dinosaurs had feathers and were warm-blooded, about the ancestry of modern birds. This high school section is largely about population genetics, and while there's nothing wrong with population genetics, it doesn't convey the big picture.

If NGSS writers were interested in pioneering, then a unit on human evolution would be the place to do it. This topic is currently mentioned in just a few state standards. Yet the hominid fossil record is as good as the Eocene horse story; the increases in brain size are intriguing, and fodder for much discussion about brains (an organ virtually absent from this document). But then, organs, and physiology in general, are virtually absent. Still, we now have Neanderthal genome data. The inclusion of human evolution would enhance the high school student's interest in evolution.

Sample problems in specific life sciences standards, now with direct emphasis on the content detail (or lack of it), are in Appendix B.

Earth and Space Sciences

The earth and space science content is quite wide, certainly adequate or better in the middle and high school. While it doesn't cover all of the content in our criteria for this discipline (see Appendix B for the content-specific criteria), it could guide a decent instructional program. It seems to have been carefully written by people who know the subject; obvious errors don't jump off the page.

There might even be too much content, *given the insistence on linking every content idea with the performance of some "practice."* Coverage of the surface processes of weathering and erosion is probably excessive—given the inadequate emphasis and treatment of deeper earth structure and processes.

As complete as the secondary content might be, the elementary content doesn't always lay the requisite foundation for its ideas. The conscious omission of minerals and rocks—both information about their formation and hands-on experience of different types and properties—leaves no scaffold for later development of the "rock record" and weathering of minerals, dating of earth events, changes to landforms over time, and so on. Earthquakes and volcanoes *receive no treatment* as phenomena (causes and effects), though they get several glancing notices (uses) in contexts such as time scales, "patterns" and hazards. Isotopes are referred to in terms of dating, but we could find no background on isotopes in the physical science sections. Earth's crust and mantle are occasionally (and importantly) referred to, but the critical concept of the layered earth in general is not offered in any systematic way.

In some cases, huge amounts of content are implied or referred to in connection with a single performance expectation! Thus the reduction in the number of standards is an illusion. Large numbers of content-performance expectations are hidden within or behind a single "standard." For example,

> *MS-ESS1-g. Apply scientific reasoning using geologic evidence to determine the relative ages of a sequence of events that have occurred in Earth's past. [Clarification Statement: Evidence can be field evidence or simple representations (e.g., model of geologic cross-sections); "events" may include sedimentary layering, fossilization, folding, faulting, igneous intrusion, and/or erosion. These kinds of events will continue to happen in the future as they have in the past.]*

In just this (rather typical) standard we have

> Sedimentary layering (though rock formation was not taught earlier)
> Fossilization
> Folding and faulting (structural geology not taught)
> Igneous intrusion (igneous rocks and processes not taught)
> Erosion (that one was done)

Meeting only this one standard implies weeks of classroom time—and is unfair to students and teachers because considerable amounts of prior knowledge are here taken for granted, yet that prior knowledge never appeared in standards for the earlier grades.

Similarly, this high school expectation is excessively broad:

> *HS-ESS1-g. Analyze actual or simulated isotope ratios within Earth materials to make valid and reliable scientific claims about the planet's age, the ages of Earth events and*

rocks, and the overall time scale of Earth's history. [Clarification Statement: Actual or simulated isotope data can be used (from materials that include igneous rocks, fossils, sedimentary layers, or ice cores) to understand how events in Earth's 4.6-billion-year history have absolute ages that can be quantified.] [Assessment Boundary: Radiometric dating techniques using complex methods such as multiple isotope ratios are not assessed.]*

In order to meet, or even teach to, this standard, one would have to assume prior knowledge of structure of the atom, atomic and molecular weights, some chemical kinetics, isotope fractionation, materials such as the crystallization of igneous rocks, how sedimentary layers form, chemical composition of the atmosphere, a hint of structural geology, not to mention the occasional exponential function. Some of it can be introduced at the time of use, but there is far too much content knowledge implied in this standard for it to serve as a discrete performance expectation.

This is a serious issue in a document that claims to be well-sequenced and coherent with regards to content knowledge. Our overall impression of the earth science standards is that there is a lot of good content in secondary but it is not supported by elementary background information. *This is explicitly a failing of the standards themselves and not something that can readily be remedied in curriculum design*.

Finally, the crosscutting concepts in earth science add little value. They are matters so general that they can be tied together in all sorts of ways—e.g., "energy" and "stability and change," which are universals. It doesn't characterize a process much to say that it involves energy flow or that it is either changing or stable!

Engineering, Technology, Applied Science

We are respectful of and, on the whole, pleased with the effort to make awareness of engineering and technology a content component of the new science standards for K–12. The method finally chosen by NGSS writers to accomplish this is to highlight (with an asterisk, and with comment as they deem appropriate) a significant fraction of all the standards that appear under the three traditional Disciplinary Cores. Various guidelines, in front matter and appendices, as well as explanatory text within the standards statements, then clarify and otherwise support the engineering connection. And, in some cases, the connection to engineering is handled quite well. Take, for example, the following:

> **MS-PS1-g Design, construct, and test a device that either releases or absorbs thermal energy by chemical processes.***[Clarification Statement: Design solutions could involve chemical reactions such as dissolving ammonium chloride, or burning a food item and measuring the temperature of water heated from the reaction.] [Assessment Boundary: Criteria other than temperature and time are not intended in testing the device.]

This involves construction of a device involving a temperature change from a chemical process, and device construction is a good engineering objective.

Unfortunately, the effort to integrate engineering and technology into the sciences is sincere is not handled consistently throughout the document. In the current draft of NGSS, the *engineering asterisk* seems to be applied to anything referring to human-made objects or tools (often associated with the word "design") or to materials or objects with a function. That use is far too liberal and seems to be quite superficial in places, particularly in life science and earth science. If technology is being used in a scientific investigation, rather than developed, then there should be no asterisk.

An incandescent light bulb is an example of a technology, but surely its use in an experimental study would not constitute an engineering and technology activity. It seems that, in some cases, the *use* of a light microscope is considered enough to warrant the engineering/technology designation. When considering technology in its context with engineering, we should be considering *technology innovation* rather than *technology application*. Technology application can be presented in the context of scientific inquiry and considered quite apart from the development of *new* technologies to accomplish a desired goal—that is, technology innovation. Only the latter is directly consistent with *engineering design*. Note that in the supplemental materials on Engineering and Technology, there is some concern about the struggle the drafters had with Core Idea 2. The first of the two sub-ideas under Core Idea 2 deals with STEM influence on society and the natural world. Essential questions for K–2 and 3–5 levels in this first sub-core idea involve *use* of technological tools. Scientific and engineering instrumentation can be quite complicated and sometimes requires significant skill for operation, so focusing on these tools is worthwhile; however; this should not be associated with engineering practice.

Another terminology issue: The word *design* is used in very different ways throughout the NGSS. It is critically important to distinguish design of a scientific study from engineering design. The former can be expressed without using the term "design" at all. Why not replace it with "develop or plan an experiment" to avoid this confusion? Again, this semantic issue is most evident in the Life Science and the Earth Science areas. *If there are only a few obvious places to legitimately include engineering and technology, then this should be acknowledged!* The objective here is not to provide window-dressing for engineering; it is to accomplish a serious and legitimate objective. The objective of engineering and technology content in NGSS should be to connect the sciences and mathematics to the needs of society via *engineering practice* and *technological innovation*.

We've included domain-specific feedback on the connections with engineering in Appendix A.

Nature of Science (Including Practices and Crosscutting Concepts)

Our judgments on the quality of the new standards on this broad and necessary topic in K–12 science are here exhibited as a set of editorial suggestions. These allow us to make clear what we consider to be the overall strengths, but also—and quite specifically—certain weaknesses of the adopted forms and emphases in standards that refer, *or ought to refer,* to scientific method and to instructive episodes in the history (and philosophy) of science.

The first paragraph of Appendix G (the "Crosscutting Concepts Matrix") remarks that the crosscutting concepts (e.g., patterns) are "not intended as additional content." But because they are so salient in the main body of the present document, readers may think that they must make sure that students can verbalize—for example—the fact that that they are studying a *pattern* in nature or a natural system. This could easily become both boring and distracting!

Appendix F ("Science and Engineering Practices Matrix") makes a similar point in the second paragraph. Although students should experience the practices of scientific inquiry, "they cannot learn or *show competence* in practices except in the context of *specific* content" [emphasis added]. *Well, yes!* In other words, students will *not really* be able, or need to be able, to articulate the difference between using a model (practice #2) and carrying out an investigation (practice #3).

Assuming that readers are now acquainted with the main features of the NGSS, they will want to look at the details of the individual DCIs, which provide examples, clarifications, and assessment boundaries. Although looking for connections between DCIs and Practices on the one hand and Crosscutting Concepts on the other hand may well have played a helpful role in the development of the content progressions, at this point we would recommend minimizing this scaffolding or even removing it entirely from the core of the report. *As now formatted, these boxes on either side of the DCIs are largely a distraction and rarely help the reader.*

Appendix H on the Nature of Science makes specific proposals about including material from the history of science and introducing students to standard scientific concepts concerning the role of observations, theories, etc. These are most worthy *additions* to the standards as given and should be brought to the attention of teachers and curriculum designers, not relegated to an appendix.

Suggestions Related to Discussions of Crosscutting Concepts

To help the reader remember the intended *positive* connotation of the strange term "Crosscutting," it would be good also to talk about bridging disciplines, analogies, and parallels—that is, to use the accustomed language.

On the other hand, the discussion of the seven Crosscutting Concepts is at times overly rosy and over-simplified. Not only do scientists look for patterns—so did Pavlov's dogs! So what is noteworthy about *patterns* in science? Why not talk instead about generalizations and classifications and then point out that we need to be on the lookout for anomalies and exceptions?

The examples of cause and effect are needlessly bland. Why not mention necessary vs. sufficient conditions? Obvious examples would be vitamin deficiencies (scurvy and rickets would be dramatic examples) and the role of oxygen in combustion. This idea also plays a major role in technology. (And children can understand it. "For want of a nail, a shoe was lost …")

An additional important concept that is not salient in the Crosscutting Concepts is the contrast between positive relations among variables (the pressure in a closed container increases with temperature) and inverse relations (the more chickens you put in a coop, the less room each has).

Some suggestions about the deployment of models appear below. The overall recommendation is to *make the terminology within the standards consistent with the prevailing use of terms within the sciences themselves*.

Two Large Terminological Confusions in "Practices"

The effort to introduce new terminology, in this case *practices*, in order to emphasize departures from traditional discussions of scientific method or scientific inquiry, sometimes leads to a lack of precision and will inhibit understanding. Let us look at some of the eight individual practices highlighted in this edition of NGSS. Given the emphasis on crosscutting and the aim of explicitly including engineering within the curriculum, the very first of these practices is puzzling. We are told that scientists ask questions while engineers solve problems.

> "The best way to tell if a practice is being used for science or engineering is to ask about the goal of the activity. Is it to answer a question? In which case, they are doing science. Is the purpose to define and solve a problem? In which case, they are doing engineering." (Appendix F, p. 3)

Trying to legislate this strange usage is counterproductive. (According to Wittgenstein, you can *call* a dog's tail a leg, but that doesn't give the dog five legs.) Scientists and philosophers have long said that a major aim of science is to solve fundamental *problems*, and we dare say they will continue to do so. Plato's "problem of the planets" was the key to the development of astronomy until the completion of the Copernican Revolution. A deep problem in physics today is coming up with a consistent quantum theory of gravity. Philosophers such as Dewey, Popper, and Kuhn talk about science as problem solving. Of course, scientists also talk about asking questions. What is dark matter and what is dark energy? *Nothing of educational value is gained by trying to draw a line between scientific questions and scientific problems.*

It makes more sense to describe engineers as folks who solve design problems but also sometimes ask open-ended questions. (After trying 1,500 different materials, Edison questioned whether there was any substance that would work in a light bulb. Until recently, engineers asked if it was possible in principle to use superconductors to transport electricity or trains.) To add to the confusion, throughout the document it is recommended that students be encouraged to *ask questions* about both scientific claims and engineering designs. Emphasis on critical thinking is admirable, but it undermines the effort to demarcate science and engineering by trying to distinguish between questions and problems! Better not to demarcate that way at all.

Practice number two is called *developing and using models*. And the word "model" is ubiquitous in these standards but with multiple denotations. Scientists themselves talk about various kinds of models, ranging from scale models in wind tunnels to elaborate computer models to model organisms—rats, mice, zebra fish, and sea urchins! But in 4-LS1 From Molecules to Organisms, p. 1, we read that students are to "develop a model using an analogy, example, or abstract representation to describe a scientific principle or design solution." So we now know that, according to the NGSS, even an example or an analogy can be considered a model! (As noted, scientists also talk about model organisms, but that is clearly *not* what is intended here.)

And the phrase *abstract representation* makes one wonder whether the standards would endorse a distinction between scientific models and scientific theories. Is Newton's Law of Gravitation now to be called a model? It is certainly an abstract representation of gravitational interactions, and—like models—it does not include other forces! *But this is needless obfuscation arising out of a felt need for abstraction*.

The confusion increases when we read about what students are supposed to *do* with a model. Here is one example amongst many: In MS-PS1 Matter and Its Interactions, p. 1, we read that students who "demonstrate understanding" can "develop a molecular level model that depicts and predicts why either temperature change and/or change of state can occur when adding or removing thermal energy from a pure substance." A challenging task indeed for a middle school student (assuming he don't trip up on being asked to "predict why"). But then we read in the Clarification Statement that while drawings and diagrams can be used, according to the Assessment Boundary, "the use of mathematical formulas is not intended." Furthermore, we are told, it is not required to show that "electrostatic interactions break when changing state."

What, then, is the intended role of models here? Is the student supposed to somehow draw a picture of molecules speeding up as heat is applied? Would sketching a rough graph of temperature of water in a teakettle as it sits on a gas flame be too mathematical? And how is the student supposed to provide a molecular model showing the heat of vaporization, especially if he has to leave out interactions between molecules?

Insistence that models play such an important role in all aspects of pedagogy can make some of the otherwise excellent DCIs either unintelligible or simply unworkable.

NGSS on the Nature of Science

Appendix H ("Nature of Science") begins with a short summary of what various groups that contributed to the *Framework* felt students should know about the nature of science. It emphasizes that students should not only have experience in doing scientific projects, but they should also need to be able to describe those experiences using standard methodological terminology.

"Students need to understand what is meant, for example, by an observation, a hypothesis, an inference, a model, a theory, or a claim and be able to distinguish among them" (Appendix H, p. 1). The document then briefly describes the Practices and Crosscutting Concepts that appear to be most closely related to the goal of having the student attain a basic understanding of the Nature of Science, and then asks,

> "Now, the science teachers' question—How do I put the elements of practices and crosscutting concepts together to help students understand the nature of science?…It is one thing to develop the practices and crosscutting concepts in the context of core disciplinary ideas. *It is another aim to develop an understanding of the nature of science within those contexts.*" (Appendix H, p.2.) [Emphasis added]

The essay in Appendix H proposes two remedies. First, the longstanding tradition of using stories and case studies from the history of science to illustrate how science works is cited with approval. Eight episodes are listed that seem particularly relevant to the K–12 curriculum, including twentieth-century discoveries, such as plate tectonics and the Watson-Crick DNA structure. The essay then indirectly admits that it is a challenge to put material on the nature of science into classrooms based on the NGSS; but it tries to be optimistic:

> "The nature of scientific explanations was proposed as the idea central to standards-based classrooms. Beginning with the practices, core ideas, and crosscutting concepts, science teachers *can progress* to the regularities of laws in importance of evidence, and the formulation of theories in science. With the addition of historical examples, the nature of scientific explanations assumes both a human face and is recognized as an ever-changing enterprise." (Appendix H, p.4) [Emphasis added]

We can well ask whether teachers *will* progress to such case studies and discussions. But even more troubling is the fact that the DCIs as currently written are so frequently expressed in terms of *modeling* or *patterns*, in contexts where traditional descriptions in terms of observations, generalizations, hypotheses, explanations, etc. seem more appropriate and more consistent with the actual *practice* of scientists.

Appendix H ends with a matrix that is intended to be linked with the array of DCIs. Most items there are clear and cogent. Two corrections need to be made, however. Specifically, comments on the nature of *scientific theories* are misleading. Given the common complaint of science deniers that a claim they dislike is "just a theory," it is very important that the standards be crystal clear on this topic.

On p. 6, middle school students are to learn, "Theories are explanations for observable phenomena" and that "the term 'theory' as used in science is very different from the common use outside of science." But then high school students are to learn, "Theories and laws provide explanations in science, but *theories do not with time become laws or facts*" [emphasis added]. The HS box goes on to speak sensibly about how theories are substantiated by observation and experiment but revisable in the light of new evidence. However, *the statement in quotation marks above is misleading* in two ways. First, it might be taken to suggest that facts and laws are *not* revisable, which is clearly false (even Newton's laws are approximations). More importantly, it suggests that theories *always* have less evidential support than laws or observation report. That is the case with newly proposed theories, but what we might call mature theories are supported by what Whewell called a "consilience of inductions"—namely, a variety of evidence drawn from many sub-disciplines. So although theories may seem more ambitious and farther from observation, they can actually be better supported than claims that are "lower" down the ladder.

IV. What Needs To Be Done

One of our reviewers conveyed, in closing her evaluation, a very few suggestions for the final revision of what we all judge to be an important and inherently valuable undertaking—the NGSS—on the imaginary condition of her being given absolute power of revision. We (sadly) do not expect the NGSS team to follow this excellent but sweeping advice. We will, however, offer it—because we all agree with it—before we descend closer to the ground.

1. Ban the use of the term "model," except in familiar scientific contexts such as molecular models or Copernican model or computer modeling (better identified as simulation).

2. Rewrite all performance expectations in plain, familiar language, without reference to Practices or Crosscutting, and put this in the main body of the publication, following a beginning section based on the relevant current Appendices that define Practices and Crosscutting and discuss their importance in K–12 science.

3. Since the *Practices* and *Crosscutting Concepts* discussions have their own considerable interest for K–12 science education, provide a good version of the arrays now available, but put them into an Appendix. If it is a good one with compelling arguments, curriculum designers will use them.

These suggestions may be too radical for this stage of the NGSS process, but they highlight what underlies a large fraction of all the "concerns" implicit in the comments provided here and in the Appendix on specific standards.

General Recommendations

We've included detailed, domain- and standard-specific commentary and feedback for the authors in the previous sections, as well as in Appendix A. In addition, we have eight broad recommendations that, if followed, would substantially improve the final version of the NGSS:

1. Acknowledge and repair the crucial content omissions (and fake compressions, and sweeping mega-standards) that are apparently caused by the desire to limit the number of standards.

2. Do away with assessment limitations that, especially in combination with content omissions, have the effect of barring access by advanced students (and their teachers) to more advanced knowledge and deeper understanding.

3. Reduce the insistent "Practices" language in the standards. Science practices certainly need to be taught and learned, but there is no justification for converting all expected science performances to "practices," and making their *substrate*, scientific knowledge (including substantive, mathematical, analytical, and vocabulary knowledge) *secondary*.

4. Remove the ambiguities and errors that we have identified above (and in the appendix).

5. Replace or provide the missing *basic* content topics (as identified in our standard-specific comments), such as thermodynamics in physics or mitosis and meiosis in Life Science.

6. Remove the more remote, fanciful connections of Engineering and Technology with science content (see above); keep the strong connections and interdependencies, and re-write all sections that attempt to differentiate Science from Engineering with such simple dichotomies as discussed above.

7. Attend to the issues of alignment with Common Core mathematics, which are treated separately but published in company with this review, and make full use of the mathematics covered in CCSSM.

Commentary and Feedback on Alignment of Next Generation Science Standards with the Common Core State Standards for Mathematics

By William Schmidt and W. Stephen Wilson

Organization of the math content in the NGSS

In the Next Generation Science Standards (NGSS), math content is presented two ways. First, at each grade level, the NGSS are divided either by "topics" (e.g., waves, energy, etc.) or by "Disciplinary Core Ideas (DCI)" (e.g., "Matter and its Interactions," "Motion and Stability: Forces and Interactions"). Beneath each topic or DCI, the authors have listed "Common Core State Standards Connections" for both English Language Arts and for math. Here, the teacher's attention is drawn to relevant Common Core content standards and mathematical practices.

In addition, the NGSS includes Appendix K, "Connections to the Common Core State Standards for Mathematics." Here, organized by NGSS "topic," connections between the Common Core and the NGSS are explained and, under each topic and for each grade, an explicit example is given intended to illustrate how the math is used with the science standard. Finally, "alignment notes" provide specific information about what math students should be expected to know and what will be introduced in later grades.

Summary

The underlying premise of this review is that the mathematics expectations of CCSSM and NGSS should be aligned, grade by grade, because a given state or district or school or teacher is apt to be dealing simultaneously with the curricular and pedagogical implications of both. Moreover, creators of textbooks, other instructional materials, assessments, pre- and in-service training for educators, and many others in and around the education system also need to know whether the math required to master the stated NGSS content is the same math—for a given grade or grade cluster—that's being taught and learned (or has already been learned) in connection with the math standards and exactly how that math is to be used in NGSS.

For those looking to examine this alignment, or to align their own curriculum planning and instruction for science with grade-level math, Appendix K is a useful document that helps bridge the two subjects.

Unfortunately, while useful, Appendix K is also incomplete. It supplies much information about the "connections" between math and science for grades K through 5, only some information on the connections between math and science at the middle school level, and no guidance or information about connections between math and science that should be made in high school.

The failure to complete Appendix K is particularly troubling, since the information included therein is far *more* useful than the math connections included in the main NGSS document. For starters, the "connections" listed in the NGSS document are nothing more than a list of relevant math practices or expectations drawn from the CCSSM. No context, alignment notes, or additional guidance is provided for teachers hoping to use math in science. Worse, at the middle and high school level, NGSS contains topics for which connections to the CCSSM should be included, but none are listed.

Further complicating matters, at the high school level in particular, both the NGSS expectations and the related Common Core standards are too broad to usefully guide planning, instruction, or assessment. More specifically, most of CCSSM connections for high school math refer not to individual standards but, rather, to math “clusters” or “domains.” The challenge is that these clusters and domains include several individual math standards, and no guidance is given as to *which* math standards should be integrated into science, or about how teachers could usefully incorporate that math content into their planning and instruction.

In short, within this draft of the NGSS itself, there is virtually no guidance about the specific mathematics to be used for individual science standards at the high school level and only occasional guidance at the middle school level.

Because Appendix K is incomplete, it does not solve the problem it was intended to solve. The solution is to complete it. Each science standard that requires mathematics should be connected to a mathematics standard *and* clear, relevant examples should be given. Without this, the mathematics alignment is unknowable

Because the present draft fails to do this, but is described as the last public draft before NGSS is finalized, much of the mathematics alignment cannot be reviewed in timely fashion. This is a regrettable situation for the writers of NGSS to be in. They should have the opportunity to get feedback on this key aspect of their work before it is graven in stone.

Details

Where Appendix K gives good coverage, it is indeed quite good. It supplies limits to the mathematics used, as well as crucial examples of how the mathematics is used for particular standards in the NGSS.

There are some minor and major issues with NGSS and Appendix K, and we review them here by going through Appendix K in order—an order that follows that of the Topics Arranged Standard version of the NGSS.

Lower School

K. Interdependent Relationships in Ecosystems: Animals, Plants, and Their Environment.
Four CCSSM items are connected to three NGSS items, but only one science example is given. More is required.

K. Weather and Climate

The science example using K.MD.1 (from CCSSM) in Appendix K for K-ESS2-a is completely unrelated to this DCI code. Another irrelevant example is given for K.MD.2.

1. Waves: Light and Sound
There is no obvious use for the math in 1.MD.1-2 in 1-PS4-e and Appendix K makes no connection.

1. Space Systems: Patterns and Cycles
CCSSM 1.OA.2 and 1 connect with 1-ESS1-a and c respectively, but no examples to make this connection are given in Appendix K.

2. Earth's Surface Systems: Processes that Shape the Earth
The science example for CCSSM 2.MD.4 is about plants, which is unrelated to the standards 2.ESS2-e and b, which are about landforms.

2. Structure and Properties of Matter
The standards connect to CCSSM MP.3,5 and 6, but these are not dealt with in Appendix K, where examples should be given.

2. Forces and Interactions: Pushes and Pulls
The connecting CCSSM standards are 2.MD.1-4, which are all about measuring and estimating lengths. These do not seem to match up much with the assessment components of NGSS. The science example given is a stretch but makes a superficial connection.

3. Interdependent Relationships in Ecosystems: Environmental Impacts on Organisms
CCSSM 3.MD.4 is used for DCI Codes 3-LS4-a,d, and 3-LS2.a, but Appendix K only gives one science example, which is not enough to illustrate the three standards it must be used for.

4. *Earth's Surface Processes*
CCSSM 4.MD.1 is used, but the example is irrelevant to the topic. The rest of the examples in this section are quite good

4. Structure, Function, and Information Processing
The CCSSM standards 3.MD.1-2 are connected to NGSS, but Appendix K does not give examples, which might be explained because they are hard to come by. Either there should be examples or there should be no connection to CCSSM.

4. Energy
Although this entire section seems to be amenable to quantitative techniques, only 4-PS3-a is connected to mathematics through CCSSM 4.OA.3. The science example in Appendix K does not connect with Energy, but is an artificial problem that includes arithmetic.

5. Structure and Properties of Matter
Only DCI codes 5-PS1-d and e are connected to CCSSM even though 5-PS1-c is explicit about "Make observations and measurements," and in the clarification, we have "both qualitative and

quantitative measurements." More connections should be made. In addition, there is nothing in Appendix K covering this.

5. Earth's Surface Systems
Appendix K nicely connects CCSSM 5.G.2 with 5-ESS2-b, but the other DCI codes could and should use a bit of elementary math as well.

Middle School

MS. Structure and Properties of Matter
Only one DCI code, MS-PS1-b, is listed in the connections, but this is done in a much broader sweep than was done in K–5. Here, this science standard is connected to two entire clusters of mathematics standards. Such connections are so broad as to be virtually meaningless. Appendix K discusses clusters 6-7.RP about ratios that were left out, and does not discuss one of the clusters, 6.SP, which was included in the NGSS, at all.

MS. Chemical Reactions
Here, there seems to be a bit of a communications breakdown between NGSS and Appendix K. Again, although it looks like lots of math could be used in this section, only the broad sweep of 6.EE and 6.SP (domains, i.e. clusters of items) are connected. Appendix K provides only one limited reference to 6.EE (A*lso represent the problem by an equation.)* and instead gives examples for the number system, 6-8.NS and 6.SP, statistics and probability.

MS. Forces and Interactions
This section of NGSS should be very mathematical, even at the middle school level. Indeed, the connections list gives more CCSSM clusters of standards than anything found previously. However, this is missing completely from Appendix K, and each connection should be clarified with a concrete example relating to the assessment component. This is a significant gap.

MS. Energy
There seem to be some typos in the CCSSM connections section here because much of the mathematics list does not mean anything in the CCSSM. Appendix K covers some of the math listed and more. However, one of the science standards, MS-PS3-a, is explicit about "...interpret graphical displays...between the kinetic energy of an object and its speed..." The appropriate interpretation is "quadratic," but CCSSM does not cover quadratics in middle school so Appendix K is reduced to "interpreting" the relationship as nonlinear. If the science represented here calls for recognizing this as a quadratic relationship, then there is an alignment issue.

MS. Waves and Electromagnetic Radiation.
The science students are expected to master requires math content that is not included in the CCSSM at the middle school level, a serious alignment problem. Appendix K unsuccessfully attempts to fix this problem. Some work is required to get NGSS and Appendix K working together properly.

MS. Structure, Function, and Information Processing
No mathematics is listed for the connection section of NGSS, but Appendix K lists 6-8.EE from CCSSM and gives relevant examples. Again, better coordination is essential.

This same problem recurs where the math referred to in the NGSS connections is not what is dealt with in Appendix K. This is true for the following middle school topics:

MS. Matter and Energy in Organisms and Ecosystems
MS. Interdependent Relationships in Ecosystems.
MS. Natural Selection and Adaptations

After this, there is no math made explicit in either the NGSS connections or in Appendix K. For the topics listed below, we presume this failure to connect the science and math is not intentional, since there are important links between the two. Those links should be made explicitly.

MS. Space Systems
MS. History of Earth
MS. Earth's Interior Systems
MS. Earth's Surface Systems
MS. Weather and Climate
MS. Human Impacts

Finally, there is a long list of math standards that support NGSS for the "MS Engineering Design" topic. Unfortunately, there is no corresponding coverage in Appendix K.

High School
As noted previously, the core problem at the high school level is that there is no equivalent of a well-done Appendix K, something that should be considered essential for these standards. The fact that it doesn't exist now means that, even if it comes into existence in the final version of NGSS, there will be no opportunity for any external review before it is promulgated—which we find seriously problematic.

Draft II of NGSS is clearly incomplete in other ways when it comes to math. For example, there are no connections to CCSSM for a number of topics that would seem to rely on math for the science to be properly taught, learned, and applied, including,

HS.History of Earth
HS.Earth's Systems
HS.Weather and Climate
HS.Human Sustainability
HS.Engineering Design

The next issue is that some NGSS standards are very broad, covering large swaths of content in a single expectation. These standards are then linked not to individual math standards, but rather to domain clusters, which include several math standards. In other words, the NGSS have written excessively broad science standards, then linked them to equally broad lists of math content, giving very little indication of either the specific science *or* math that students need to learn. And the failure to link to *specific* math standards, the “connections” give little more than a broad directive to “include math,” which is no little better than making no attempt to link science and math.

HS. Structure and Properties of Matter
This first high school topic illustrates the alignment problem between the NGSS and the CCSSM. One cluster, CCSSM F.LE, "Construct and compare linear, quadratic, and exponential models and solve problems" is linked to HS-PS1-c, "Analyze and interpret provided data about bulk properties of various substances to support claims about the relative strength of the interactions among particles in the substance." There is no way of knowing how this math standard might be used with the science standard without an explanation or example.

Other omissions:

HS.Chemical Reactions
Again, most of the math connections here are about statistics. However, NGSS HS-PS1-h discusses proportions while linking only to a general algebra equation CCSSM standard, not to standards about proportions. Similarly, scientific notation would seem to be essential here, but there is no math connection to that.

HS. Forces and Interactions
This should be one of the more mathematical sections of NGSS. However, the standards do not even mention *F=ma*. The several references to the CCSS math standards are either to clusters of standards or to vague general standards. There is no indication of what is actually expected of a student mathematically.

Finally, some connections are simply off the mark:

HS. Waves and Electromagnetic Radiation
Standards HS-PS4-a and b require some basic trigonometry as Snell's law is referenced explicitly. The many links to CCSSM are to broad categories of standards. For example, the reference that does include some trigonometry is to F.IF, which has 9 standards plus another 7 sub-standards. The trig is included in just the last of 5 sub-standards for standard number 7. The CCSSM section on trig functions, F-TF, is not referenced at all. There is a real lack of specificity about the mathematics that is to be used with the NGSS standards here.

The Potential Value of a Completed and Perfected Appendix K

We have several times referenced the incompleteness of Appendix K, particularly in regard to middle and high school science, as well as a few glitches found in what it does cover. It’s also important to underscore and illustrate what is valuable in Appendix K, which does much more than just link the science standards to the math standards. Its best parts also give concrete examples of the use of the mathematics standard in the science standard. Here, a half-dozen examples show the great benefit to teachers of this kind of supplementation.

3.WC Weather and Climate
The science examples linked to CCSSM 3.MD.2 are, "(1) Estimate the mass of a large hailstone that damaged a car on a used-car lot. (2) Measure the volume of water in liters collected during a rainstorm."

The example linked to CCSSM 3.MD.3 is, "Make a picture graph or bar graph to show the number of days with high temperature below freezing in December, January, February, and March. How many days were below freezing this winter?"

3.IVT Inheritance and Variation of Traits: Life Cycles and Traits
This is linked to CCSSM 3.MD.3 and the science example given is, "Make a scaled bar graph to show the number of surviving individuals with and without an advantageous trait. How many more of the individuals with the advantageous trait survived?"

3.FI Forces and Interactions
CCSSM 3.MD.2 is connected with the science examples: "(1) Estimate, then measure, the masses of two objects being used in an investigation of the effect of forces; observe that the change of motion is larger for the smaller mass (students need not explain or quantify this observation in terms of Newton's laws of motion). (2) When the reservoir of a model dam is filled to capacity, measure the volume of water in liters that flows over the dam when a known volume of water in liters is poured into the reservoir. Observe that the two volume measures are equal and that the water level is the same afterwards as it was before. Model this with a subtraction sentence such as $V + 2 - 2 = V$ (adding 2 liters and subtracting 2 liters did not change the volume of water in the reservoir)."

4.ESP Earth's Surface Processes
CCSSM 4.MD.1, 2, 4, and 5 are illustrated, respectively, with the following examples:

- (4.MD.1) "know that 1 ft is 12 times as long as 1 in. Express the length of a 4 ft snake as 48 in. Generate a conversion table for feet and inches listing the number pairs (1, 12), (2, 24), (3, 36)."

- (4.MD.2) "0.2 kg of topsoil was lost from a square meter of farmland due to erosion over the course of a year. If 60 g of topsoil was deposited during that year, what was the net gain or loss in grams? What will happen if this pattern continues each year?"

- (4.MD.4) "from a line plot find and interpret the difference in length between the longest and shortest specimens in an insect collection."

- (4.MD.4) "Use paired line plots to show the mass of soil displaced by flowing water with and without vegetation, using several trials in each condition (measurements would likely be in whole numbers of grams or ounces)."

- (4.MD.5) “Measure the angle of incline in an investigation of erosion by flowing water; make an accurate sketch showing several different angles of incline.”

4.W Waves
CCSSM 4.G.1 has example: “Identify rays and angles in drawings of wave propagation.”

5.SS Space Systems: Stars and the Solar System
CCSSM 5.G.2 connects with the following examples:

- “(1) Over the course of a year, students compile data for the length of the day over the course of the year. What pattern is observed when the data are graphed on a coordinate plane, and how can a model of the sun and Earth explain the pattern?”
- “(2) Students are given (x,y) coordinates for the Earth at six equally spaced times during its orbit around the sun (with the sun at the origin). Students graph the points to show snapshots of Earth’s motion through space.”

Appendix A: Standard-Specific Issues

I. Physical Science

> **K-PS1-c. Ask questions, based on observations, to classify different objects by their use and to identify whether they occur naturally or are human-made.*** [Clarification Statement: Patterns include the similar characteristics of objects that determine whether they occur naturally or are human-made.]

This jams together two things that are not necessarily related. Classifying objects according to their use is quite different from classifying them by their natural or artificial origin. For example, a goose quill and a ballpoint pen can be have roughly the same use; a sewing needle and a hypodermic needle have quite different uses.

> **2-PS1-d. Identify arguments that are supported by evidence that some changes caused by heating or cooling can be reversed and some cannot.** [Clarification Statement: Examples of reversible changes are melting chocolate or freezing liquids. An irreversible change is cooking food.]

Here, as in Draft 1, melting chocolate is a very poor example. Chocolate does not melt in the strict sense of the word; it merely changes its viscosity (as glass also does). Why not pick something unambiguous, like ice?

> **5-PS1-a. Argue from evidence to support the theory that matter is made of particles too small to be seen.** [Clarification Statement: Examples of evidence could include adding air to a basketball, compressing air in a syringe, or moving air on a piece of paper.]

How do the given examples exemplify the statement? Even the most likely example, compressing air in a syringe, involves some pretty sophisticated hypotheses.

Worse, this expectation simply restates examples that do *not* support atomism. It's not by accident that, as late as the end of the nineteenth century, some distinguished physicists (e.g., Ernst Mach) were still skeptical of the atomic theory of matter. It was only in 1905, with Einstein's theory of Brownian motion and Perrin's work on colloids, that the scientific community was finally and definitively convinced. "One of the things which distinguishes ours from all earlier generations is this, that *we have seen our atoms*."

-Karl K. Darrow, *The Renaissance of Physics* (1936). (Note the date!)

There is nothing wrong with *telling* students that matter is made of tiny particles. 5-PSI-b, immediately following, does exactly this with conservation of mass in chemical reactions. But it is wrong to pretend that they have the evidence for atomism to hand at this grade level.

> **MS-PS1-b. Design a solution that solves a practical problem by using characteristic chemical and physical properties of pure substances.*** [Clarification Statement: Real world problems could involve the need to test for water quality, or mineral content of ores. Properties of substances can include melting and boiling points, density, solubility, reactivity, reaction with oxygen, and phase at a given temperature.] [Assessment Boundary: Limited to simple common substances (e.g., sodium chloride, sugar, sodium bicarbonate, calcium chloride, water, methane, propane, hydrogen, oxygen, steam).]

How is the middle school student supposed to test for water quality or mineral content of ores using "characteristic chemical and physical properties of pure substances"?

> **MS-PS1-c. Develop a molecular level model that depicts and predicts why either Temperature change and/or change of state can occur when adding or removing thermal energy from a pure substance.**

The concept of thermal energy is a tricky one to distinguish from temperature, and to understand in its own right. It deserves some fairly detailed exposition before it is applied to an example such as this one. We have seen nothing of the sort. One way to deal with this would be in the context of atomic theory, which is also short-changed. In any case, atomic theory and thermal energy are closely linked topics and deserve much more careful exposition than is given here.

> **PS3.A: Definitions of Energy: 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. (secondary to MS-PS1-c)**

Something is wrong here—perhaps a proofreading error. It is certainly high time at the middle school level to define energy in a careful if not definitive way, but this does not do it. Moreover, it is restricted to thermal energy; we have seen no attempt to discuss mechanical energy at all. In any case, it would be wise to use the word "heat" very carefully. In the context of the first law of thermodynamics, energy can be transferred from one system to another either in the form of work or in the form of heat, the latter embracing everything but the former. One sometimes speaks of the heat energy of an object, but it is better to call it internal energy—the kinetic and potential energy involved in the internal motion of the object's molecules.

HS-PS1 seems to cover a wide swath of chemistry, but on a purely qualitative level.
For example,

> **HS-PS1-e. Construct an explanation about the effects of changing the temperature or concentration of the reacting particles on the rate at which a reaction occurs.** [Clarification statement: Evidence will come from temperature, concentration, and rate data; student reasoning should include that the factors that affect reaction rates depend on the number and the energy of the collisions between molecules.] [Assessment Boundary:

Limited to simple reactions in which there are only two reactants. The quantitative relationship between rate and temperature is not required.]

This might be satisfactory for a ninth-grade general science course of some sort, but is far too low-level for high school chemistry. And we haven't seen a single chemical equation!

(HS-PS1-d) Stable forms of matter are those in which the electric and magnetic field energy is minimized. A stable molecule has less energy, by an amount known as the binding energy, than the same set of atoms separated; one must provide at least this energy in order to take the molecule apart.

This is the first mention seen of magnetic field energy. But magnetic field energy has little to do with chemical bonding; it is significant in the matter of spin alignment in magnetic materials, which is a rather different thing. Why is magnetic energy dragged in by the ears here?

PS3.C: Faster speeds during a collision can cause a bigger change in shape of the colliding objects. (secondary to 2-PS2-a)

"Faster speeds," like "warmer temperatures," is a barbarism. When an object goes faster, we say that it has a higher speed; when an object is warmer, we say that it has a higher temperature. In science standards, using scientifically appropriate language is critical.

Similarly, standard (3-PS2-a) indicates: "A system can appear to be unchanging when processes within the system are going on at opposite but equal rates."

Why not use the proper technical terms, dynamical equilibrium or steady-state equilibrium?

MS-PS2-a. Develop a graphical or physical model, based on Newton's Third Law, to test solutions to a practical problem by predicting the motion of two interacting objects.*
[Clarification Statement: Examples of practical problems could include safety tests on cars that collide with other cars or stationery objects; or the impact of a meteor on a space vehicle.] [Assessment Boundary: Restricted to vertical or horizontal interactions in one dimension.]

It makes sense to introduce Newton's law of motion in middle school. But the Clarification Statement is more in tune with the law of momentum conservation (which involves the time-integrated forms of Newton's laws.) The phraseology "Develop a graphical or physical model …" serves only to confuse the issue.

MS-PS2-b. Design an investigation to produce empirical evidence supporting the claim that the change in the motion of an object depends on the sum of the forces on the object and the mass of the object.

This is confusingly phrased. One does not (and cannot) add forces and masses. Just add "…and *on* the mass of the object." The following Assessment Boundary puts $F = ma$ off limits, which makes sense at this level. But having set forth Newton's first and third laws, it would make sense at least to make a loose qualitative statement of the second law as well. Acceleration as a quantitative entity is likely too advanced for many middle school students, but the idea of change in velocity can be presented, perhaps in the familiar context of riding in automobiles.

> **MS-PS2-c. Ask questions about data to clarify the factors that affect the strength of electric and magnetic forces to improve the performance of an electromagnetic device.*** [Clarification Statement: Devices could include electromagnets, electric motors, or generators. Empirical data can include measuring the effect of the number of turns of wire on the strength of an electromagnet, or the effect of increasing the number or strength of magnets on the speed of an electric motor.] [Assessment Boundary: Assessment of Coulomb's Law is not intended.]

There are several problems here. First, one cannot "ask questions about data" so as to "affect the strength …" Maybe one can simply "Clarify the factors …" and leave it at that.

Second, and more important, Coulomb's law has nothing at all to do with the strength of an electromagnet, or any of the other matters in this item.

> **MS-PS2-d. Construct and present oral or written arguments that use evidence to support the claim that gravitational interactions determine the motion of systems of objects in space.** [Clarification Statement: Evidence for arguments can include charts displaying mass, strength of interaction, distance from the sun, orbital periods of objects within the solar system, and various examples of why objects with horizontal velocity fall into the earth versus why satellites don't fall into the earth.] [Assessment Boundary: Quantitative arguments are not assessed. Newton's Law of Gravitation is not assessed. Evidence for arguments is given to students.]

Amid all the verbiage are two possible meanings. One, presumably not desired, is "Parrot back the limited information the teacher has given you." A second, not much better, is "Make sense out of a bunch of bits of information the teacher has given you in random order."

> **MS-PS2-e. Design, conduct, and evaluate an investigation that will gather evidence that force fields exist between objects exerting forces on each other, even though the objects are not in contact.** [Clarification Statement: Evaluating an experimental design refers to evaluation of an experiment's ability to provide the data necessary to meet the goals of the experiment. Examples of this phenomenon could include the interactions of magnets, electrically-charged strips of tape, electrically-charged pith balls, and objects at varying distances from the earth or on different planets (which can be investigated through simulations).] [Assessment Boundary: Fields included are limited to gravitational, electric, and magnetic. Determination of fields is qualitative, not quantitative.]

What is “field” supposed to mean at the middle school level? A field is defined in terms of the force experienced by a test object at any location relative to the source. But this is useful only in a quantitative context. At this level, all one can really say is that a charge (for instance) is seen to experience a force in the vicinity of another charge, from which one may infer that in some other location it will experience a force, likely different in magnitude and direction. This is not really an “investigation that will gather evidence that force fields exist.” Rather, it is at best a generalization made from a series of observations, which may lead to a *definition* of “field.” In any case, what’s the point in “defining” a field – an abstract concept – at this level?

Forces that act at a distance (gravitational, electric, and magnetic) can be explained by force fields that extend through space and can be mapped by their effect on a test object (a ball, a charged object, or a magnet, respectively). (MS-PS2-e)

But the real logic goes in the other direction. This could be neatly fixed simply by substituting “described” for “explained.” Fields *describe* forces; they don’t *explain* them.

> **MS-PS2-f Define a practical problem that can be solved through the development of a simple system that requires the periodic application of a force initiated by a feedback mechanism to maintain a stable state.*** [Clarification Statement: Examples include a weather vane or a wind sock at an airport.]

A wind sock is *not* a good example of periodic application of a force. What’s periodic about the force? A much clearer example would be a child pushing another child on a swing in such a way that the swinging amplitude remains constant.

> **(PS2-b) The greater the mass of the object, the greater the force needed to achieve the same change in motion.**

It would be good to add “net” force here.

> **MP 4** Model with mathematics (MS-PS2-a)
> **6.RP** Understand ratio concepts and use ratio reasoning to solve problems. (MS-PS2-c)
> **6.EE** Apply and extend previous understandings of arithmetic to algebraic expressions. (MS-PS2-e)
> Represent and analyze quantitative relationships between dependent and independent variables. (MS-PS2-e)
> **7.RP** Analyze proportional relationships and use them to solve real-world and mathematical problems. (MS-PS2-c)
> **7.EE** Solve real-life and mathematical problems using numerical and algebraic expressions and equations. (MS-PS2-b), (MS-PS2-c)
> **8.EE** Understand the connections between proportional relationships, lines, and linear equations. (MS-PS2-c)

These links with mathematics are fine. But none of the ones cited above are actually employed in the core material here. To the contrary, Assessment Boundaries clearly warn us off quantitative (let alone algebraic) exercises!

> **HS-PS2-a. Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on macroscopic objects, their mass, and acceleration.*** [Assessment Boundary: Restricted to one-dimensional motion and to macroscopic objects moving at non-relativistic speeds.]

We get to an actual quantitative exercise using Newton's second Law. But why phrase it in this obscure way? Why not "Measure the motion of gliders on an air track and show that the motion is well described by Newton's second law of motion, $F = ma$." The restriction to nonrelativistic speeds will then take care of itself; it's hard to exceed 10^8 m/s on an air track.

> **HS-PS2-b. Use mathematical expressions to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system.** [Clarification Statement: Conservation of momentum is the focus. Using mathematical expressions includes explaining the meaning of those expressions. Desired quantities are the total momentum of the system before and after interaction.] [Assessment Boundary: Systems are restricted to two macroscopic bodies moving in one dimension.]

Mathematical expressions will never support such a "claim." Measurements will.

> **HS-PS2-d. Use mathematical expressions to represent the relationship between the variables in both Newton's Law of Gravitation and Coulomb's Law, and use these expressions to predict the gravitational and electrostatic forces between objects.** [Clarification Statement: Using mathematical expressions includes specifying relationships in both quantitative and conceptual terms.]

As stated, this is nonsense. Newton's law of gravitation and Coulomb's law are mathematical expressions, and the form of the expressions automatically represents the relationship *among* (not between) the variables.

If one could escape the math phobia shown throughout these standards, one could make this perfectly clear simply by writing:

$$F = G\, m_1 m_2 / r_{12}^2; \qquad F = 1/4\pi\varepsilon_0 \; q_1 q_1 / r_{12}^2$$

> **HS-PS2-e. Design and conduct an investigation to support claims about how electric and magnetic fields are created.**

Claims? Created? This is not a theological document. How about, "Show by experiment how one can produce an electric field by rubbing a glass rod with a piece of fur and a magnetic field in the vicinity of a current-carrying wire." And it would be really nice here, at the high school level, to *define* a field rigorously; e.g.; $E = F/q_t = 1/4\pi\varepsilon_0 \; q_s/r_{st}^2$

HS-PS2-f. Produce technical writing and/or oral presentations about why the molecular-level structure is important in the functioning of designed materials.

What does this have to do with **HS-PS2 Motion and Stability: Forces and Interactions?**

> Momentum is defined for a particular frame of reference; it is the mass times the velocity of the object. (HS-PS2-b)

Here again, we see a statement that makes more sense in reverse: Momentum is defined as the product $p = mv$ of the mass of an object and its velocity. Since velocity is defined only for a specified frame of reference, momentum must be defined within a particular frame.

> **4-PS3 Energy Students who demonstrate understanding can: 4-PS3-a. Construct an argument using evidence about the relationship between the change in motion and the change in energy of an object.** [Assessment Boundary: No attempt is made to give a precise or quantitative definition of energy. Students should not be assessed on quantitative measures of changes.]
>
> **4-PS3-b. Make observations and collect data to provide evidence that energy can be transferred from place to place by sound, light, heat, and electric currents**. [Assessment Boundary: Quantitative measurements of energy are beyond the scope of assessment.] 4-
>
> **PS3-c. Formulate questions and predict outcomes about the change in energy that can occur between colliding objects and/or magnet interactions.** [Clarification Statement: Emphasis is on the change in the energy, not on the forces, as objects interact.]

At this level, it is certainly reasonable to supply the limitation "No attempt is made to give a precise or quantitative definition of energy." But some kind of definition is in order, if only something like "Energy is what gets things done." Absent this, students are studying something that has a name but no distinct meaning.

> **(4-PS3-a) The faster a given object is moving, the more energy it possesses.**

But this is untrue of, say, a body falling under the influence of gravity. As it falls, it goes faster and its kinetic energy increases. But its potential energy decreases by the same amount. And to skim over this is to put a stumbling block in the way of a later understanding of conservation of mechanical energy.

A lot of this hand waving could be sidestepped by early introduction of the simple concept of work – force multiplied by the distance over which it is applied. Formal treatment of the work-energy theorem can wait till high school, but the idea that doing work on something increases its energy can be useful at a much earlier stage.

> **5-PS3-a. Use models to describe that energy animals use to maintain body warmth, body repair, and for motion was once energy from the sun.**

Here is another example (among many) where the stock phrase “Use models to describe that” conveys no information and merely serves to obfuscate.

> **MS-PS3-a. Construct and interpret graphical displays to describe the relationships between the kinetic energy of an object and its mass, and between the kinetic energy of an object and its speed, in order to better define a real world problem.*** [Clarification Statement: Data are provided to students. Examples could include riding a bicycle, rolling a rock downhill, and getting hit by a hardball versus a tennis ball.] [Assessment Boundary: A focus on calculating kinetic energy from the equation is not intended.]

Here is an example of deliberate and counterproductive avoidance of a quadratic relationship.

> **MS-PS3-b. Develop models to describe that when the distance between objects within a system changes, electrical, gravitational, or magnetic fields store different amounts of potential energy.** [Clarification Statement: Examples of systems in different configurations could include: the Earth and either a roller coaster cart at varying positions on a hill or objects at varying heights on shelves, an iron nail being moved closer to a magnet, and a balloon with static electrical charge being brought closer to a classmate’s hair. Examples of models could include representations, diagrams, pictures, or written descriptions of systems in different configurations.] [Assessment Boundary: Quantitative calculations are not required.]

Energy has not been defined; potential energy has not been defined; field has not been defined, and quantitative calculations are off limits, but the poor middle school student is expected to understand the concept of potential energy of a field—and develop models. College senior physics majors have trouble with the concept of field potentials.

> **MS-PS3-d. Design an investigation to determine the relationships among the energy transferred, the type of matter, the amount of sample, and the resulting change in temperature of the sample.** [Clarification Statement: Examples of experiments could include comparing final water temperatures after different masses of ice melted in the same volume of water with the same initial temperature, the temperature change of samples of different materials with the same mass as they cool or heat in the environment, or the same material with different masses when a specific amount of energy is added. Experiments can be designed individually and collaboratively.] [Assessment Boundary: Calculations of specific heat capacity or thermal energy transferred are not assessed.]

Why not something clear, like the following: “By performing experiments with various quantities of various substances, and with ice in water, develop a qualitative understanding of the concepts of heat capacity, specific heat capacity, and latent heat.”

> **MS-PS3-e. Use and present written arguments that contain evidence to support the claim that when the motion energy of an object changes, energy is transferred to or from the object.**

This is backward. A much better recommendation would be, “Show how doing work on an object changes its energy.”

> **MS-PS3-f. Develop models to represent that plants produce sugars by reacting carbon dioxide and water and absorbing energy, and that the opposite process occurs in plants and animals to release energy.**

Another example of obfuscation by “Practices”: What, other than confusion, does the phrase “Develop models to represent that…” introduce?

PS3.A: Definitions of Energy

> **Motion energy is properly called kinetic energy; it is proportional to the mass of the moving object and grows with the square of its speed. (MS-PS3-a)**
>
> **A system of objects may also contain stored (potential) energy, depending on their relative positions. For example, energy is stored—in gravitational interaction with Earth—when an object is raised, and energy is released when the object falls or is lowered. Energy is also stored in the electric fields between charged particles and the magnetic fields between magnets, and it changes when these objects are moved relative to one another. (MS-PS3-b)**

This is a definition students can use.

The following passage correctly states that temperature is a measure of the mean kinetic energy of the molecules of a substance, but no justification is given. And PS3-C almost—but not quite—gets to the work-energy theorem, which should come before all the rest.

> **HS-PS3-a. Use mathematical expressions to describe, model, or simulate the change energy in the energy of one component within a closed system when the change in the energy of the other component(s) is known.**

We have no idea what this means and the Clarification Statement that follows is no help.

> **HS-PS3-c. Develop a model that supports the explanation that all forms of energy can be described as either the movement of particles or energy in fields.**

What kind of “explanation” is it to say that energy is energy in fields?

HS-PS3-d. Design and conduct an investigation to support the claim that the transfer of thermal energy between components results in a more uniform energy distribution among the components of a closed system.

Hidden in this statement is the zeroth law of thermodynamics—when a warmer and a cooler body are in thermal contact, there will be heat flow from the warmer to the cooler until the two are at the same temperature. Why make it harder than it is?

HS-PS3-e. Develop and use models of two objects interacting through a field to explain the changes in energy and the forces between the objects due to the interaction. [Clarification Statement: The emphasis of the core idea is on the relative position, not mass or charge. Representations could include drawings, diagrams, and texts. An example would be drawings of what happens when two charges of opposite polarity are near each other, including an explanation of how the change in energy of the charges is related to the change in energy of the field.]

The Clarification Statement still doesn't inform us of what the student might be expected to do.

HS-PS3-g. Evaluate the benefits and drawbacks of nuclear processes compared to other types of energy production. [Clarification Statement: Students are provided with data and information (e.g., input/output data, production, storage costs) about energy production methods (e.g., burning coal or solar energy generation versus using nuclear reactors.] [Assessment Boundary: Students only evaluate data and information provided. Benefits and drawbacks only include economic, safety, and environmental.]

The totality of the preceding material, the science content backup, hardly provides the student with a basis to do this.

The DCIs PS3-A and PS3-B purport, here at the high school level, to define energy and energy conservation. But they slide over the subject and don't come close to the straightforward and fairly simple explanation that can be presented to high school students in a physics course.

The presentation of waves at Grades 1, 4, and 5 is fine. It lays the foundation for the student's intuitive understanding of wave phenomena. But at the middle school level we have:

MS-PS4-a. Design an investigation to produce data that support the simple model for waves, including how the energy in a wave depends on the amplitude. [Clarification Statement: The simple model for waves describes waves in terms of wavelength, frequency, and amplitude, and explains what happens when waves pass through each other.]

What does "the simple model for waves" mean? It is not at all clear what investigation or what data are implied. Perhaps the student is expected to understand that waves can be described in terms of the medium in which they exist, their speeds, their wavelengths (or frequencies), and their amplitudes. But if that is the case, *why not just say so*?

Interference is introduced (very briefly) in MS-PS4-b. This is desirable, but perhaps a little expansion would be in order.

> **A simple wave has a repeating pattern with a specific wavelength, frequency, and amplitude. (MS-PS4-a)**

But the wave speed (which depends on the medium and the type of wave) is also important, as is clear if we write the very simple relation $v = f\lambda$.

> **HS-PS4-a. Make quantitative claims using provided data regarding the relationship among frequency and wavelength, and the speed of the wave traveling in various media.** [Clarification Statement: Examples of provided data could include electromagnetic radiation traveling in a vacuum and glass, sound waves traveling through air and water, and seismic waves traveling through the Earth. Relationships are only expressed algebraically.]

This is a complicated and confusing way of saying $v = f\lambda$! (But note that EM radiation does not necessarily travel in a medium, as the standard implies.)

The Assessment Boundary for HS-PS4-b is confusing, since it is not easy to experiment with the law of reflection or Snell's law using sound waves.

II. Life Science

> **MS-P3 Energy: PS3.D. Both the burning of fuel and cellular digestion in plants and animals involve chemical reactions with oxygen that release stored energy.**

This is not correct. Oxygen (O2) serves as the terminal electron/proton acceptor in respiratory electron transport chain. Chemical reactions with oxygen do not occur during cellular digestion (whatever that means; we assume metabolism of food). Molecules are often oxidized, which means that electrons/protons are taken from one molecule and transferred to another (which is reduced), and sometimes the participating atoms include oxygen in various chemical configurations (hydroxyls, ketones); but this statement suggests an equivalence of the burning of a hydrocarbon and metabolism that is not correct.

> **4-LS1-c Construct models to describe that animals' senses receive different types of information from their environment, process the information in the brain, and respond to the information in different ways.** [Clarification Statement: Examples of models could be diagrams or analogies.] [Assessment Boundary: Students are not expected to know the mechanisms by which the brain stores and recalls information, nor the mechanisms of how sensory receptors function.]

One can imagine drawing a diagram of a human with ears, drawing some musical notes with arrows going into ears and then more arrows into head, and drawing the human responding with dance steps. Is **that** a model? Does this "demonstrate understanding"? Specifically, would it indicate that I understand anything about senses, brains, or responses to sensory input? There's far more sophisticated information in the DCI below this (LSD.1) but none of it is reflected in the task.

> **MS-LH1-h. Analyze and interpret provided <u>data</u> to generate <u>evidence</u> supporting the <u>explanation</u> that plants may continue to grow throughout their life through the production of new plant matter via photosynthesis.** [Clarification Statement: Emphasis is on a conceptual understanding that plant growth continues throughout the life of plants via photosynthesis and not on the details of the mechanisms that enable plants to grow. The data may be from investigations, simulations, or archived data.] [Assessment Boundary: The assessment should measure students' abilities to interpret the data that does or does not support the idea that plants grow throughout their lives via photosynthesis.]

One's pot-bound house plants typically *do not grow*, nor do stressed plants in general, *but they are alive and doing photosynthesis*.

Moreover, a mixed message here: first we're told that plants ***may*** continue to grow throughout life; then we are supposed to understand that plant growth ***does*** continue throughout life (not *may* continue); then we're supposed to interpret data that does or does not support the idea.

What data are to be provided? If we're given data, *what* does it mean to generate evidence? Aren't the data the evidence? In what way is the statement that plants may continue to grow throughout their life an *explanation*?

> **MS-LH1–k Develop a model to support the explanation that within an individual organism food moves through a series of chemical reactions in which it is broken down and rearranged to form new molecules, to support growth, or to release energy.** [Clarification Statement: Emphasis is on a conceptual understanding of the cycling of food and the release of energy and how it is used in organisms. The energy released from the food is used by the organism for life processes.] [Assessment Boundary: The assessment should provide evidence of students' abilities to use a model to explain the cycling of matter in an organism, the input and output of that matter, and that some of those molecules become part of the organism. Details of cellular respiration or the chemical reactions describing photosynthesis or respiration are not assessed.]

We fail to understand how a series of chemical reactions is depicted without "details" of chemical reactions. Is the student expected to draw a red rectangle depicting one molecule and a green rectangle to depict its "broken-down rearranged" version? Why prevent her/him from drawing the real thing?

Moreover, the metabolism of food is only indirectly related to respiration and *not at all to photosynthesis*. And why phrase it as “release energy” rather than “form energy-rich compounds like ATP” (remarkably, ATP does not appear throughout this document). “Release energy” sounds like giving off heat, which of course happens but that’s not the point of food consumption.

> **MS-LS1-m. Gather, read, and communicate information for how the storage of long-term memories requires changes in the structure and functioning of interconnected nerve cells in the brain.** [Clarification Statement: Students can evaluate the source of the information that could be used to obtain reliable information about memory and brain function and communicate a conceptual explanation of the structure function relationships of how the brain is able to store long-term memory.]

Accompanied by LS1.D: Each sense receptor responds to different inputs (electromagnetic, mechanical, chemical), transmitting them as signals that travel along nerve cells to the brain. The signals are then processed in the brain, resulting in immediate behaviors or memories. Changes in the structure and functioning of many millions of interconnected nerve cells allow combined inputs to be stored as memories for long periods of time.

If a middle school curriculum were to offer adequate resources for gathering and communicating information about changes in the structure and functioning of interconnected nerve cells in the brain that generate storage of long-term memory, that curriculum would need to cover synapses, neurotransmitters, ion channels, depolarization and hyperpolarization, dendritic spines, cAMP formation, and protein kinase activation—for openers. Even then, these proximate understandings of events that accompany memory formation leave vast lacunae in understanding the process since it’s not at all understood how language works, how memory retrieval works, how consciousness works. We do not find it credible that a middle school student who is restricted from conveying any in-depth understanding of metabolic/biosynthetic pathways is somehow supposed to approach this truly challenging topic in neuroscience.

MS-LS1 Science and Engineering Practices.

Here are a few sentences from this section:

1. Use and/or develop models to predict, describe, support explanations, and/or collect data to test ideas about phenomena in natural or designed systems, including those representing inputs and outputs, and those at unobservable scales.
2. Design an investigation individually and collaboratively, and in the design: identify independent and dependent variables and controls.
3. Gather, read, and communicate information from multiple appropriate sources and assess the credibility, accuracy, and possible bias of each publication and methods used.

Even veteran biologists would have little to no idea how to approach these exercises. What is meant by inputs and outputs? What is an unobservable scale? How are independent and dependent variables predicted a priori in the design of an investigation? Such relationships are discovered by doing the experiment and analyzing the resultant data. How does a middle school student assess the credibility, accuracy, and bias of a source when it's a major challenge for a professional?

HS-LS1 All content challenges multiply at the high school level. Two examples from HS-LS1: Students are expected to *critically read scientific literature and communicate* on

a. transmission of neural impulses, muscle contraction, and blood glucose levels; and
b. how DNA sequences determine the structure and function of proteins.

Depth level for (a) includes chemical reactions that take place between different types of molecules (water, proteins, carbohydrates, lipids, nucleic acids (albeit "emphasis is not on biochemistry"), and depth level for (b) is to convey major conceptual ideas of the process that lead to protein synthesis (*albeit the specific steps of transcription and translation or actual protein structure are not assessed*). How does one describe biochemistry without biochemistry? How does one describe protein structure without describing "actual" protein structure? And, most disturbing for this standard, how can a high school student read *critically* actual scientific papers, always terse and full of specialized vocabulary, on these topics given these assumptions of shallow background and preparation?

> **HS-LS1-d Design and conduct an investigation to gather evidence in supporting explanations for the function of feedback mechanisms to maintain homeostasis.** [Clarification Statement: The emphasis is on investigations (e.g., heart rate response to exercise, blood vessels response to temperature changes) that students use to provide evidence to support explanations of types of feedback.] [Assessment Boundary: The assessment should provide evidence that students can distinguish between evidence supporting the feedback mechanism and evidence that does not include a feedback mechanism. Additionally, students should be able to determine whether or not an investigation is safe and ethical. The assessment should provide evidence of students' abilities to distinguish between supporting and irrelevant data. Cellular operations involved in the feedback mechanism are not assessed.]

On what basis is a student expected to be able to determine whether or not an investigation is safe and ethical?

> **HS-LS1-e. Use a model to support the explanation of how mitotic cell division results in daughter cells with identical patterns of genetic material essential for producing and maintaining a complex organism.** [Clarification Statement: Emphasis is on conceptual understanding that mitosis passes on genetically identical materials via replication, not on the phases of mitosis.] [Assessment Boundary: The assessment should provide evidence of students' abilities to explain from a model (e.g., diagrams, computer simulations) how cells may have differentiated within an organism but are genetically identical.]

HS-LS1-f. Construct an explanation using evidence for how cell differentiation is the result of activation or inactivation of specific genes and small differences in the immediate environment of the cells; relate these concepts to potential solutions in biomedical engineering and research.* [Clarification Statement: Emphasis is limited to the concept that a single cell develops into a variety of differentiated cells and thus, a complex organism.] [Assessment Boundary: The assessment should provide evidence of students' abilities to construct an explanation about the conditions necessary for cell differentiation as well as the applications for biomedical research (e.g., cancer treatment, replacing damaged organs, engineering tissues to test drugs).]

HS-LS1-g. Develop and revise a model to support explanations about the role of cellular division and differentiation in producing and maintaining complex organisms composed of systems of tissues and organs that work together to meet the needs of the entire organism. [Clarification Statement: Emphasis is on the concept that genetically identical cells produced from a single cell during embryological development differentiate and become tissues that make up organs within organ systems working together to meet the needs of the organism.] [Assessment Boundary: The assessment should provide evidence of students' abilities to show strengths and/or limitations of a model to demonstrate the development of differentiated cells with specific functions necessary for the organism to survive. Assessments could use a computer simulation. Emphasis is not on recalling the steps of mitosis or specific gene control mechanisms.]

In the three standards referenced above, how does one discuss replication without some concept of mitosis? Isn't it easier to just learn the stages—each one makes a lot of sense—rather than to convey that doing so isn't needed? What is meant by "small differences in the immediate environment of cells"?

HS-LS1-h. Develop a model to support explanations for how photosynthesis transforms light energy into stored chemical energy. [Clarification Statement: Emphasis is on model development within the context of explaining the process of photosynthesis. Models may include diagrams and chemical equations. The focus should be on the flow of matter and energy through plants and other photosynthesizing organisms.] [Assessment Boundary: The assessment should provide evidence of students' abilities to describe the inputs and outputs of photosynthesis, not the specific biochemical steps.]

HS-LS1-i. Construct an explanation that carbon, hydrogen, and oxygen from sugar molecules produced through photosynthesis may combine with other elements to form amino acids and other large carbon-based molecules. [Clarification Statement: Emphasis is on students constructing explanations for how sugar molecules are formed through photosynthesis and the components of the reaction (i.e., carbon, hydrogen, oxygen). This hydrocarbon backbone is used to make amino acids and other carbon-based molecules that can be assembled into larger molecules (such as proteins or DNA).] [Assessment Boundary: The assessment should provide evidence of students' abilities to explain the relationship between the products of photosynthesis and their role as building blocks for the formation of macromolecules. Limited to the conceptual understanding of how the products of photosynthesis are utilized to build macromolecules. The details of the various chemical reactions are not assessed.]

Even in high school the students are expected to have only a vague idea about photosynthesis (the "inputs and outputs")? We can understand not *memorizing* the steps of the Calvin cycle, but just inputs and outputs? *They did that in middle school*.

HS-LS1-k. Produce technical writing to communicate information about the evidence from technologies that supports explanations for the integrated functioning of various regions of the brain.* [Clarification Statement: Emphasis is on evaluating evidence about the integrated functioning of various regions of the brain and the technologies (e.g., MRI, CAT scan) used to gather the evidence about how the brain functions.] [Assessment Boundary: The assessment should provide evidence of students' abilities to determine which explanations are supported by valid and reliable data and the sources of the data. Emphasis is on physiological function, not the value of the behavior to the organism.]

Perhaps the writer here is the same one who expected middle school students to understand memory storage, but the expectation that a high school student could read about MRI and CAT scans and then demonstrate the ability to determine which explanations are supported by valid and reliable data is stunning.

2-LS2-b Define a simple problem and test solutions to determine which better fulfills the function of an animal necessary for the reproduction of a flowering plant. [and our point is?]

This sentence is incomprehensible.

3-LS2-a: "Systems are groups of animals." What can this mean?

5-LS2-b,d "Minerals and fertilizer are not food for plants." "Air, water, and minerals (fertilizer) are needed by plants but are not food for them."

While this may be technically correct using one definition of food, one fails to understand the emphasis on this idea. And when we get to "Students should be assessed on the idea that plants make their own food from materials that are not food (air and water), not the process of photosynthesis," we are genuinely puzzled—don't they make their own food via photosynthesis?

Heredity: Much of the language of the standards on heredity is likely to cause a teacher to conclude that the specifics of heredity are not nearly as important as its broadest generalizations. If the only important concept is that traits are passed from generation to generation (understood millennia ago) and that things called genes are involved (understood 200 years ago), this field might be conveniently small for student learning. Instead, vast quantities of detail now exist on how it all works, where for sexual organisms—for example—this entails a close understanding of meiosis, *which is proscribed*. There are too many such occasions, in which critical facts and ideas are given a gloss at best.

> **MS-LS3 LS3A: Each chromosome pair containing two variants of each of many distinct genes.**

In many cases both chromosomes in a pair will carry two genes that are *not* variants; that is called homozygosity.

> **MS-LS3 LS3A: Each distinct gene chiefly controls the production of specific proteins.**

Each gene controls the production of a single protein (unless the writers have splice variants in mind, which is very unlikely, that being from advanced molecular genetics).

> **MS-LS4-d Analyze graphical displays to compare patterns of similarities in the embryological development across multiple species to identify relationships not evident in the fully formed anatomy.** [Clarification Statement: Emphasis is on comparing patterns that appear as gross similarities and differences to provide evidence of general relationships among organisms that are more or less related.] [Assessment Boundary: These comparisons are limited to general characteristics of early embryological development of related species.]

This document gives no acknowledgment that students, let alone middle school students, will be taught anything about embryos other than the confusing gloss that in multicellular organisms cells differentiate as the consequence of genetic instructions and small differences in the immediate environment of cells. Will they know enough about *embryogenesis* to be able to compare patterns of similarities in the embryological development across multiple species?

III. Engineering

Engineering content in the NGSS has been—wisely—integrated with performance expectations for each scientific discipline. We include some specific feedback on this integration below, organized by NGSS topic.

PS1 Matter and Its Interactions

Generally, the engineering approach is well covered here; however, some of the language used and assumptions made are questionable. The term "natural material" is used in 2-PS-1 to refer to natural resources from which human-made products are fashioned, but later the term "natural resources" is used. Why not set the vocabulary and stick to it? A child may not comprehend the fact that raw materials used to make the products they see may have gone through a complex set of changes, often at a scale smaller than what they can see (perhaps at the level of atomic structure.

5-PS1-e Generate and compare multiple solutions that meet the desired criteria of improving a property of a material within the constraints of changing the type of substances, the amount of substances used to make the material, and the temperature at which they are mixed.*

How will teachers know how to implement demonstrations such as this?

MS-PS1-b Design a solution that solves a practical problem by using characteristic chemical and physical properties of pure substances.* [Clarification Statement: Real world problems could involve the need to test for water quality, or mineral content of ores. Properties of substances can include melting and boiling points, density, solubility, reactivity, reaction with oxygen, and phase at a given temperature.] [Assessment Boundary: Limited to simple common substances (e.g., sodium chloride, sugar, sodium bicarbonate, calcium chloride, water, methane, propane, hydrogen, oxygen, steam).]

The word "design" is used loosely such as in developing a simple test for chemical or physical properties of materials.

It is not obvious that using the word "design" in the engineering context is constructive when it is done without evaluating multiple approaches and doing so within constraints.

The term "model" seems to be used throughout MS-PS1-d in different ways starting at the elementary levels.

HS-PS1-g Refine the design of a chemical system to specify changes in conditions that would produce increased amounts of products at equilibrium.* [Clarification Statement: Examples of designs could include different ways to increase product formation including adding reactants, or removing products. Designs should include descriptions of the connection between changes made at the macroscopic level and what happens at the molecular level. Examples of chemical systems could be nitrogen plus hydrogen producing ammonia or reactions in which water is produced – such as a simple condensation reaction.] [Assessment Boundary: Limited to simple reactions provided to students, adding or removing one reactant or product at a time. Calculating equilibrium constants and concentrations is not included. The effect of temperature on equilibrium is not included. Quantitative changes are not required.]

This is a very useful design activity in which students seek to increase the production of a chemical equilibrium product, but it does not need to be a quantitative study. *Why not* make this quantitative at this level?

PS3 Energy

PS3. Defining energy is a very difficult issue and the definition in PS3 does not seem adequate. Richard Feynman pointed out rather clearly that we don't really know what energy is, *though we can account for it quantitatively.* What is clear in the classical/macroscopic sense is that energy is possessed as mass and various other forms of internal energy (encompassing microscopic kinetic energy, rotation, vibration, nuclear spin, electron spin, chemical bonds, etc.), as well as in external kinetic and potential energy associated with the system center of mass in the presence of fields. Energy changes are ascribed to *energy flows* such as heat, absorption/emission of light, work, and energy flows associated with the flow of mass across a system boundary. These are important concepts that are very difficult for students to understand clearly. PS3 should be reconsidered very carefully.

PS4 Waves and Their Applications in Technologies for Information Transfer

This section seems fine in general; however, in 5-PS4-a students consider the use of light optics in microscopes. There is no mention of the fact that (visible) light is not useful for seeing matter at length scales smaller than (approx.) the micron level, i.e. the resolution limit, due to the wavelength, prevents us from observing objects smaller than the major components of living cells. We cannot observe atoms or molecules with light microscopes, so the associated crosscutting statement (MS-PS4 Structure and Function) should be qualified. This is an engineering constraint on the design of microscopes! (The engineering solution is to use a form of radiation with a shorter wavelength. There are no effective lenses for X-rays, but high-energy electrons can be used in electron microscopes.) All this begs for discussion in the standards.

Life Sciences

The life sciences section has serious deficiencies with regard to the engineering and technology designations. There are numerous instances where the designation is used appropriately, but quite a few cases where it is justified by the *use of technology* for a scientific study.

For example, why is there an engineering asterisk attached to the following:

> **MS-LS1-a Design and conduct an investigation to provide evidence that living things are made of cells that can be observed at various scales.*** [Clarification Statement: Emphasis is on recognizing the strength of evidence from investigations supporting the core idea that living organisms are made of cells. It includes knowledge of ways to observe cells and ways to make observations of the results of cell functions (e.g., carrots becoming crisp when in fresh water but limp in salt water, vegetative reproduction of cutting of a plant). Students should understand that higher scale magnification provides additional information about cells that cannot be seen at lower magnification; and that such discoveries led to medical treatments for diseases such as sickle cell anemia.] [Assessment Boundary: Assessments should provide evidence of students' abilities to identify evidence that living things are made of cells, distinguish between living and not living cells, and explain the interdependence of science, engineering, and technology.]

This involves experimental planning rather than engineering design. The use of a microscope as an investigation tool should not be simply identified as engineering since the microscope is being used, not being designed. Engineering in this section should be tied to biochemical engineering and biomedical technology.

HS-LS1-k is very oddly worded:

> **"*Produce technical writing to communicate* information about the evidence from technologies that supports explanations for the integrated functioning of various regions of the brain.*"**

Any time a student writes to communicate scientific or engineering findings in a science class it necessarily involves "technical writing." Why not simply shorten this to "Communicate information about …"?

2-LS2-b, MS-LS2-c, HS-LS2-c, and MS-LS4-c do not seem to involve engineering, although they are labeled with asterisks. The solutions being tested or explanations are purely scientific ones.

Earth and Space Sciences

Many of the outcomes in this section are improperly marked as having engineering and technology content. Some of these cases are itemized below.

1-ESS1-b is marked with an asterisk because students evaluate different tools to be used for celestial observation. This is not about developing technology and is not engineering, so should not be marked as such. *There is no need to force elementary subject matter to appear as engineering or technology when it is purely science-based!*

The use of tools for scientific study is important, and discussion of tools and their evolution can provide some general ideas about a role of engineering in the progress of science, but only if the engineering development of a tool is actually taken up.

HS-ESS1-g lacks engineering content or technology development, so it should not have an asterisk.

HS-ESS2-b is focused on scientific investigation of human-influenced changes to the earth, but not on the engineering of solutions needed to intervene, so it is not at all clear that this should be marked with an asterisk.

HS-ESS2-c has an asterisk and concerns scientific investigation of the nature of the earth's interior. Where is the engineering or technology development here?

HS-ESS2-e should not have an asterisk as it involves scientific investigations of cause and effect.

HS-ESS2-I should not have an asterisk. Evaluating the role water plays in moving energy or minerals in the Earth's systems is a scientific endeavor. Using this for societal needs or intervening in some manner to protect our environment would involve engineering and technology, but that is not the specified task.

MS-ESS3-h involves scientific interpretation of data and projection of future patterns to inform the public, but does not indicate any engineering activity or involve the development of new technology, so there should not be an asterisk.

HS-ESS3-a has an asterisk, but should not. This is an historical assessment of the impact of natural resource availability on human societies.

Appendix B: Content-Specific Criteria for Science Disciplines

Our science reviewers developed criteria that delineated the essential content that should be included in rigorous, K–12 science standards in the traditional disciplines of physical science, life science, and earth science. Following are the content-specific criteria used to evaluate state science standards in 2011–12 and employed by the same reviewers in their examination of the draft Next Generation Science Standards.

Introduction to the K–12 ***Science Criteria***
In an effective standards document for K–12 science, instruction in the proposed content for grades one through eight 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/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.

Science Content: General Expectations for Learning through Grade Eight

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[2]

Between ninth grade and high school graduation, many (but not all) students take only one full, two-semester science course. Others may take an "integrated" science course or courses. Elective opportunities, including AP courses, are widespread. The expectations shown here must, therefore, be read selectively and with care. The physics content shown, for example, is primarily, but not necessarily, limited to students who have taken high school physics

High School 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.

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[2] Note that in the grades K-8 standards, physics and chemistry content is combined under the heading "physical science." At the high school level, these important standards should be broken out and standards for physics and chemistry should be presented separately. Our criteria reflect this change.

- 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 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.

Endnotes

[1] Ref. Framework
[2] The enabling Framework was, however, somewhat dismissive of the evidence for Inquiry Learning as an effective driver of pedagogy in K–12 science.
[3] Ref. PRG Am. Educator paper.
[4] See Susan Haack, *Evidence and Inquiry: A Pragmatist Reconstruction of Epistemology* (Expanded Edition). (Amherst, NY: Prometheus Books, 2009).
[5] Appendix A, p. 2.