Review of the National Research Council's Framework for K-12 Science Education

By Paul R. Gross
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Foreword by Chester E. Finn, Jr., and Kathleen Porter-Magee

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

Science will soon join the short list of K-12 subjects for which American states, districts, and schools will have the option of using new, multi-state (aka, "national") academic standards rather than standards developed by individual states. One can reasonably surmise that new assessments aligned with those standards will follow in due course, as will curricula, professional development, textbooks, and much more.

Is this a good thing for American students and teachers—and for the nation's future? It depends, of course, on whether the new standards (and ensuing assessments, etc.) are better than those that states have been devising and deploying on their own. Today, every state has its own unique version of K-12 science standards. A year or so from now, however, many of them are apt to be deciding whether to replace their individual standards with the new multi-state standards that a (privately funded) consortium of organizations (led by Achieve, Inc.) recently began to draft.

The Task at Hand

When those "common" standards are ready, we at the Thomas B. Fordham Institute will review and evaluate them. In the meantime, we are completing our review of existing state science standards and planning to publish those evaluations later this year. (This will be the fourth time that Fordham has reviewed state science standards. To see our 2005 reviews, head here.) We are laying the groundwork to assist states when the time comes to consider adopting the new "common" science standards, just as we did in July 2010 for the Common Core State Standards Initiative (CCSSI) in English language arts and math.

But unlike the Common Core standards, whose authors scoured the nation and the world for evidence and advice regarding essential content and rigor in those subjects for the K-12 grades, the drafters of science standards at Achieve are beginning with an anchor document—the *Framework for K-12 Science Education* that was released by the National Research Council (NRC) in July 2011. One must assume that Achieve is taking the Framework seriously: Its staffers have repeatedly said they are!

At this time, we've no idea how the common science standards will turn out. But we *can* gauge the quality of the primary source that Achieve and its partners are using to determine the content and emphases of the standards they are constructing.

How reliable a guide is that document to the essential content of K-12 science? And even if it's solid on content, how good a job does it do of presenting that content in clear, usable form? To what extent does it immerse that content in a sea of jargon? Of extraneous issues? Random musings? And is there useful advice to be given to the standards-writers who are relying on that Framework as they determine which of its elements to take most seriously and how best to translate it into workable standards for actual schools and teachers?

We set out to answer those questions by turning, once again, to one of America's most eminent scientists, Paul R. Gross, who has been a lead reviewer of state and national (and international) science standards and frameworks for Fordham since 2005. (A synopsis of his résumé and qualifications appears below.) We asked Dr. Gross to apply the same basic criteria to the NRC Framework that he and his colleagues have employed when looking at other science standards and frameworks and to share the results of that review with us and the public. If it's to be a seminal document in this field—all 283 pages of it—Americans deserve to know its strengths and weaknesses.

We're well aware—and in this review Dr. Gross reminds us—that what the NRC has promulgated is a "framework," not a set of actual standards for schools, curricula, teachers, and pupils. But its authors aren't shy about suggesting that their Framework ought to undergird future K-12 science education across the land. They assert that what they've delivered consists of "the key scientific practices, concepts, and ideas that all students should learn by the time they complete high school" and that this Framework is "intended as a guide for those who develop science education standards, those who design curricula and assessments, and others who work in K-12 science education."

Key Findings

Strength in Content

What did Dr. Gross find? A lot that's good and strong, timely and useful. He gives the document as a whole a more-than-respectable grade of B-plus and, when it comes to content and rigor alone, he gives it top marks: seven points out of a possible seven. He terms the Framework "an impressive policy document, a collective, collaborative work of high quality, with much to recommend its vision of good standards for the study of science."

In particular, Dr. Gross finds that, like the best of extant K-12 science standards, the NRC Framework's authors have captured nearly all of the content that is critical to a rigorous K-12 science curriculum—real content, too, not what some critics want to dismiss as "science appreciation." The progression of this content through the grades is intelligently cumulative and appropriately rigorous. He also observes that, to their credit, the authors "wisely dismiss what has long been held indispensable for K-12 science: 'inquiry-based education.'"

Risks in the Rest

That's the good news. But, unfortunately, that's not the end of it. Dr. Gross also finds the strong content immersed in much else that could distract, confuse, and disrupt the priorities of framework users, even though substantial portions of the "much else" have some merit.

He suggests, for example, that engineering and technology may be given undue prominence, and he cautions that too much attention is paid to "science process" skills. He finds, in the Framework's protracted discussion of "equity and diversity"—especially in its emphasis on differentiating content and pedagogy—the risk of contradicting the Framework's own core mandate, which is to frame *the same* science content for all young Americans. To ensure that the standards that this Framework informs don't end up suffering from the overreach and sprawl that plague far too many existing state versions, standards-writers must make some critical decisions about priorities that were not made by the authors of the Framework itself. It's this risk of distraction, dilution, and diffusion that leads Dr. Gross to award the Framework just one out of three possible points for "clarity and specificity" (hence the B-plus grade overall).

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

Decisions Ahead

The NRC Science Framework, then, fits into the familiar category of valuable products that are best used carefully, with due attention to users' manuals, reviewers' comments, and consumer cautions. Think of a model train that works beautifully so long as the tracks are properly laid. Picture a restaurant at which you can eat a terrific meal—nutritious, tasty, balanced, and economical. If careless, however, you may find yourself neglecting the good stuff and consuming more than you should of tempting but far less nutritious fare.

And so we at Fordham, with warmest thanks to Dr. Gross for swiftly carrying out this careful, thoughtful, literate review, and to the Carnegie Corporation of New York (for underwriting our reviews of science standards and frameworks), offer this advice to users of the NRC Framework now and in the future: Select carefully.

One more thing. As we at Fordham have repeatedly noted, even the best of academic standards don't guarantee better education or more learning unless accompanied by rigorous, well-chosen, and well-aligned curricula, instruction, and assessments. Yet standards are a crucial first step toward raising—and harmonizing—our expectations of what students across the country should know and be able to do. And in K-12 science, as important a subject as one could name for our children and grandchildren to learn well and for our country to prosper, the NRC Framework reviewed by Dr. Gross is a welcome asset and boost to what we hope and expect will be the development of top-notch academic standards for U.S. schools in this vital field of study.

About the Author

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

Acknowledgments

Again, we extend deepest gratitude to science reviewer Dr. Paul Gross for his insightful and timely work on this review. This review wouldn't have been possible without the support from the Carnegie Corporation of New York and our sister organization, the Thomas B. Fordham Foundation. A resounding "thank you" also goes out to the crack Fordham Institute staff who worked hard and fast getting this review ready for primetime: to Chester E. Finn, Jr. and Kathleen Porter-Magee for their smart edits, to Janie Scull for production, and to Tyson Eberhardt and Joe Portnoy for dissemination. The clean copyediting is courtesy of Erin Montgomery.

Introduction and Background

> "Critical thinking is not a set of procedures that can be practiced and perfected while divorced from background knowledge. Thus it makes sense to consider whether students have the necessary background knowledge to carry out a critical thinking task you might assign."[1]
>
> ~ Daniel T. Willingham

The new *Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* is a big, comprehensive volume, carefully organized and heavily documented. It is the long-awaited product of the Committee on a Conceptual Framework for New K-12 Science Education Standards. Contributions have been made to this already-large committee's work by sundry advisers. The Committee, its auxiliaries, and the production program are functions of the National Research Council (NRC), a division of the United States National Academies of Science.

Advisers included both individual specialists and other participants in the—now decades-long—writing, revision, and implementation of standards for K-12 science in the United States. The Framework is not, however, an actual set of standards, nor can it be so employed. It is meant to serve as a new and authoritative resource, setting forth indispensable principles, the most appropriate K-12 science content, and heuristic samples of good standards. The expectation is that it will inform and direct the creation of new "national" (i.e., multi-state) standards.

As noted, it is a weighty document (more than 300 crowded pages), in places meticulous, not only on the customary issues of standards-writing, but also on broader, more ramified issues of K-12 education in the U.S. The Committee believes, evidently, that its charge requires full attention to these less science-substantive questions.

Content and Beyond

The document addresses not only the fundamental question of science standards, which has been and clearly remains *content selection*—what foundational science is to be taught and learned in school, and how?—but also the needs in K-12 science for the following (among others):

- Better implementation measures across the science education system, for example, in student support, teacher development, assessment[2]
- New initiatives to ensure "Equity and Diversity in K-12 Science and Engineering Education"[3]

- Philosophical and sociological background, as well as practical advice derived from it, for standards-developers
- "Research to Inform Implementation and Future Revisions of the Framework"[4]

Some of the proposed research would be of aid in verifying (or possibly refuting?) assumptions made by the writers of this Framework and already incorporated in their recommendations. The Framework notes, for example, that "the research base on learning and teaching the crosscutting concepts is limited. For this reason, the progressions we describe should be treated as hypotheses that require further empirical investigation."[5]

In this review, our foremost interest is the specific expectations for teaching and learning proposed or suggested in the document, and therefore such official standards and curricula *as are likely to result from its advice*. Whether those standards are to be prepared by science-education staff of individual states or by Achieve, Inc. for the NRC is immaterial.[6]

Content knowledge—our focus here—is identified in this Framework with a set of "Disciplinary Core Ideas." Conscientiously articulated, they include familiar topics from the three now-traditional K-12 science domains (Physical, Life, and Earth/Space Science), plus a new, fourth group, "Engineering, Technology, and the Applications of Science." Inclusion of engineering and technology as subject matter of science is not new. In weaker forms, it was present in predecessors of this Framework and is present today in some state science frameworks. We consider below the validity of the Framework's current argument for an independent and greatly strengthened position of engineering and applied science within an already time-pressed science curriculum.

As in earlier contributions from the same sources, certain cognitive and behavioral "scientific (and engineering) *practices*"[7] and several overarching themes, here dubbed "crosscutting concepts" (examples: *Patterns*, *Stability and Change*), are identified as essential parts of what is to be taught explicitly. Practices and Crosscutting Concepts are therefore two of the Framework's "Dimensions" of science education.[8] A third group of (four) Dimensions is the ingathering of all "Disciplinary Core Ideas." A summary table of the Dimensions is reproduced below. (Unfortunately, the Framework's Table of Contents lists six Dimensions, while the explanatory Box ES.1 treats the four disciplinary content Dimensions as one. This is a trivial but annoying confusion. We reproduce here both the relevant sections of the Framework's Table of Contents and the Table of Dimensions.) We must appraise the justifications given for the additions, as in Dimensions 1 and 2, to science content coverage (that is, to Dimension 3, or Dimensions 5-8 as shown in the Table of Contents).

We are concerned also with conceptual novelty, as that may or may not be present in these recommendations. The reason: claims of novelty from authoritative and respected sources, such as the NRC and the American Association for the Advancement of Science (AAAS), inevitably affect the way curriculum-makers—at state, district, and school levels—respond to the recommendations. The Framework's Introduction offers at its

Framework Table of Contents

PART II: Dimensions of the Framework

Box ES.1: The Three Dimensions of the Framework

1. Scientific and Engineering Practices

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

2. Crosscutting Concepts

1. Patterns
2. Cause and effect: Mechanism and explanation
3. Scale, proportion, and quantity
4. Systems and system models
5. Energy and matter: Flows, cycles, and conservation
6. Structure and function
7. Stability and change

3. Disciplinary Core Ideas

<u>Physical Sciences</u>

PS 1: Matter and its interactions
PS 2: Motion and stability: Forces and interactions
PS 3: Energy
PS 4: Waves and their applications in technologies for information transfer

<u>Life Sciences</u>

LS 1: From molecules to organisms: Structures and processes
LS 2: Ecosystems: Interactions, energy, and dynamics
LS 3: Heredity: Inheritance and variation of traits
LS 4: Biological evolution: Unity and diversity

<u>Earth and Space Sciences</u>

ESS 1: Earth's place in the universe
ESS 2: Earth's systems
ESS 3: Earth and human activity

<u>Engineering, Technology, and the Applications of Science</u>

ETS 1: Engineering design
ETS 2: Links among engineering, technology, science, and society

start *A New Conceptual Framework*, a "new vision for science and engineering education."[9] In early responses, the relevant media tend to associate *New* with *Conceptual*. It is the Framework's *concept* of science education that is taken to be new, not simply its temporal position in the sequence of K-12 science advisories from this agency. Novelty, as everyone knows, can be a virtue; but not, as some know, *ipso facto*. And, as we shall see, there turns out to be less here that is truly new than commentators (and perhaps the drafters themselves) may wish to believe.

Doing It Like Scientists

There has been much ado in K-12 science-teaching literature over the past quarter-century, including that part of it produced under the aegis of the Framework's sponsors, about an urgent need for students to learn science by *doing* it, rather than (merely) acquiring its facts, theories, and principles. This should by now have been recognized as a simplistic dichotomy that, in several versions, including insistence on the primacy of "inquiry-based" learning, has plagued science standards across the nation. It has certainly been responsible for many bad sets of state standards.[10]

Getting hold of the facts of science is and has always been, cognitively, a multi-step accomplishment, not just a matter of remembering terms and assertions. This insight was already implicit in James B. Conant's distinguished *Science and Common Sense*, published sixty years ago.[11] Three of the inseparable components of *knowing* science are:

> (1) acquiring (and having in one's memory) an adequate collection of observations (i.e., facts) and procedures. (Take this example of a science fact: "Well-defined, inheritable, visible characteristics, or 'traits,' of living things can 'skip a generation.'");
>
> (2) confirming that such statements are indeed factual. (Thus in the same example: recognizing, from data and experiments of genetics, that generation-skipping of traits *does happen* in a wide variety of living things); and
>
> (3) applying those facts to the search for new facts, in wider areas of experience. (In the example: the facts of generation-skipping are shown to be consistent with other facts and with the still-expanding *theory* of heredity.)

It is not at all clear (to us, at least) that today's standard-issue K-12 science education consists mostly of memorizing isolated facts. Competently delivered, science knowledge contains all three of the components listed above—and probably always has, beginning long before teachers were admonished to have their pupils learn science by "doing it."

Among the *doings* of science stressed in this Framework and its predecessors are cognitive skills with frequently used names like *scientific reasoning*, *scientific inquiry*, and *critical thinking*.[12] Their meanings are highly overlapping. If these are to be specific Dimensions of science to be taught, learned, and distinguished from science *facts*, then we must consider the evidence for their separability (pedagogically speaking) from facts. That evidence, however, is thin to nonexistent in modern cognitive psychology.

Consider Willingham: “Data from the last thirty years lead to a conclusion that is not scientifically challengeable; thinking well requires knowing facts…critical thinking processes such as reasoning and problem solving are inextricably intertwined with factual knowledge that is stored in long-term memory (not just found in the environment).”[13]

Therefore, in This Review…

…we begin with, and pay most attention to, the content recommendations, their structure, their justifications, their considerable strengths and few weaknesses. That is the burden of “Content and Rigor I,” just below. We then touch (in “Content and Rigor II”) on some but not all of the accessory discussions and recommendations provided in the Framework—those broader issues mentioned above—with emphasis on likely responses to them by standards-writers and, perhaps more important, by curriculum- and lesson-planners closer to the classroom: the true field of action. A combination of judgments on all these questions produces a letter grade, as is expected from reports like this. More important, however, than any point score or letter grade should be this (our) judgment:

The new Framework is an impressive policy document, a collective, collaborative work of high quality, with much to recommend its vision of good standards for the study of science. But that judgment also notes a few flaws. They do not undermine the good work on science subject matter, but some of them have the potential for diminishing—at waypoints in the course from framework to standards to lesson-plans—the potentially constructive effects of the Committee’s labors.

Content and Rigor I: How Much?

"A mile wide and an inch deep" has been the derisive catchword on current K-12 science education in virtually every official proposal on science standards from the NRC, from the AAAS, from groups of science teachers, and from the standards-writers of most states during the ascendancy—the last two decades—of standards-based education. What, then, does this new Framework offer as remedy for the reputed malady of breadth without depth? This: that K-12 science (now including engineering) education *must focus on a limited number* of disciplinary core ideas and crosscutting concepts, the depth of learning in each to be *progressive* as grade succeeds grade.

No serious teacher of science would disagree with the last recommendation: progressive depth. The "rigor" mentioned above is the measure of depth and level of abstraction to which chosen content is pursued. But is it true that K-12 science in the U.S. has been so shallow, so thinly spread, attempting to cover scattered fact to the exclusion of comprehension and of skills acquisition? This question can't be answered immediately with a simple yes or no. But we can get a sense, indirectly at first, of the general truth of this claim, and then return to the direct question.

Content Doesn't Just Expand: It Is Also Pruned

The putative rigidity and fixation of prior (and current) science curriculum on scattered facts to be memorized is misleading. There has always been a certain *fluidity* of content in science education. Important new *ideas* are pushed by enthusiasts for admission to the curriculum, thus expanding it.[14] But there are always arguments about which older ideas and vocabulary should then be eliminated. And they *are* eliminated. We have seen such changes in recent times with the appearance in good biology standards of population and molecular genetics, as well as of ecology and environmental science, and with the reduction in curricula of more traditional topics such as descriptive botany and comparative anatomy. Similarly, new emphasis on atomic and molecular physics in chemistry, and the insertion of "modern" (early twentieth-century) physics in the physical science syllabus, has been accompanied by reductions elsewhere.

Sometimes such intrusions go too far. Sometimes change is too stubbornly resisted. But the fluidity is a good thing, because science is ceaselessly expanding and self-correcting. Moreover, such changes cannot be solely in the form of isolated facts added (or subtracted). The additions are about ideas. And, formal reviews of all state science standards during the past two decades have *not* found remarkable demand for rote and memorization. The sadly abundant mediocre and failed state standards have usually been so judged because of deficiencies in facts and principles (see endnote 12).

Thus the "limitation" advocated by the Framework's writers cannot—and in the end does not—really mean drastic reduction of the already-limited range of required subjects found in today's best K-12 standards. This Framework employs forty-four Core Ideas. But the 2009 science Framework of the National Assessment Educational Progress (NAEP), here cited with favor, derived its *assessable* science content from a very limited set of about eighteen *core* ideas, and it ends with a practical, worked-out set of about 125 potential assessment topics. The TIMSS (Trends in International Mathematics and Science Study) framework settles on about fifty—for its eighth-grade assessment. Competent efforts to define a limited set do seem to have come up with numbers like those just mentioned. And most of those efforts cite as authority prior standards issued by the NRC! In Fordham's continuing science-standards reviews, we have identified—in seeking as close to a basic, minimum set of standard-eligible topics as possible—some fifty items. So further big reductions of core ideas or scope are unlikely. Keeping the number of standards practically small is no new concept. It *is*—and has been generally accepted as—reasonable, for almost two decades.

That said, we find in the new Framework a credible, even admirable set of thoughtfully limited core ideas of science. An example: the recommended Core and Component Ideas (remember, these are *not* standards, just ideas upon which standards are to be built) for the Physical Sciences as tabulated in Box 5-1, which we reproduce here.[15]

Box 5-1: Core and Component Ideas in the Physical Sciences

Core Idea PS1: Matter and Its Interactions
- PS1.A: Structure and Properties of Matter
- PS1.B: Chemical Reactions
- PS1.C: Nuclear Processes

Core Idea PS2: Motion and Stability: Forces and Interactions
- PS2.A: Forces and Motion
- PS2.B: Types of Interactions
- PS2.C: Stability and Instability in Physical Systems

Core Idea PS3: Energy
- PS3.A: Definitions of Energy
- PS3.B: Conservation of Energy and Energy Transfer
- PS3.C: Relationship Between Energy and Forces
- PS3.D: Energy in Chemical Processes and Everyday Life

Core Idea PS4: Waves and Their Applications in Technologies for Information Transfer
- PS4.A: Wave Properties
- PS4.B: Electromagnetic Radiation
- PS4.C: Information Technologies and Instrumentation

Note that it includes four Core Ideas, each of which expands to either three or four sub-ideas (components, topics), each of which will be the eventual subject of one or more explicit standards. There are listed, in this way, *thirteen* “component ideas” for K-12 physical science, ranging from “Structure and Properties of Matter” (PS1.A) to “Information Technologies and Instrumentation” (PS4.C). The corresponding number of topics at this level of generality for Life Sciences is fourteen; for Earth and Space Science, twelve; and for Engineering, Technology, and Applications, five. Thus we have the forty-four broad (major) learning expectations mentioned, from the identified core disciplines alone. That *is* a “limited” set (compared to the coverage in a typical set of textbooks on these subjects). But the limits are well chosen and generally consistent with the best of this Framework’s antecedents.

The Framework, in describing its component topics, also provides “grade-band endpoints.” These are statements specifying the depth, hence the level of detail, to which each of these topics should be covered by the completions of second, fifth, eighth, and twelfth grades. The arrangement is practical, and the scientific justifications offered are serious. By the measure of the vast body of *potential* core-level topics in modern science—that is, at the same level of generality as employed here—“limited” is a fair enough description.

There are, however, additional forms of “limitation” discussed in the Framework that are meant to keep in check any tendency toward inappropriate expansion. These are the (sample) proposed —and important —*Boundary Statements* for the grade bands.[16] They are provided in just two *illustrations* of performance expectations (standards): one for LS1.C. in Life Science, the other for PS.1.A. in the Physical Sciences. The statements amount to advice on what *not* to include in a grade-span, because it is judged to be unnecessary, or not grade- or age-appropriate.

What ought to be left out is as much a discretionary and debatable judgment as what ought to be in. But on the strength of these samples, the Committee expects a very large number of choices of this kind from standards-writers using the Framework. Thus for the band comprising sixth through eighth grades, one illustrative Boundary statement includes: “…forces and structures within atoms and their role in the forces *between* atoms are not introduced, nor are the periodic table and the variety of types of chemical bonds.”[17] This is indeed a limitation on the breadth of physical science instruction (and expectations!) through eighth grade, *thereby* a limit upon how much else can be taught and learned, up to that point, about the elementary particles that dominate contemporary physics and cosmology.

Such a limitation is open to discussion, particularly as its “out-year” implications for science education are pondered. Very likely, other qualified commentators favor introducing the periodic table or chemical bonds by eighth grade. But that is a matter of professional (scientific and educational) opinion, and choices must be made. The Framework undertakes to justify its choices about leaving intra- and inter-atomic forces (and atomic properties that generate the periodic table of the elements) to later, possibly advanced courses in physical science. Justifications for the choice lie in the surrounding text. *In actual standards*, boundary statements are supposed to be similarly justified. But there will always be differing views among competent standards-writers about what the grade-level boundaries should be, especially for relatively advanced topics.

Of course, decisions about what to offer and what to omit in the lower and middle grades have large effect on what can happen in high school. A full set of standards that includes such "boundary" statements can control intellectual challenge, vocabulary, and the number of performance expectations. But boundaries as here employed will remain, in many cases, choices, such that equally good sets of standards might differ somewhat at this level of detail.

A good framework proposes reasonable limitations and undertakes to justify them. This new Framework is better on science content than its influential predecessors. Care has been taken with the science writing. For example, note the thoughtful handling, by comparison with other frameworks and standards, of evolutionary biology. There is (always) room for argument about what topics are left out that should have been in, and vice versa. (There is some grumbling, for example, about the paucity in this Framework of the indispensable mathematics—strikingly indispensable, today, in all the life sciences *as well as* in the Physical, Earth and Space, and Engineering disciplines.[18]) In general, though, the Framework deals seriously with the problem of content: representativeness of the chosen subject matter and appropriate *rigor*, which is the issue of expected depth of understanding, by grade, of the selected disciplinary ideas. The scientific content in this framework is on the whole well chosen, sufficiently complete, and suitably rigorous to form the basis of excellent K-12 science standards.

Content and Rigor II: Emphases

There is more to be said, however, about content and rigor. As indicated, the choice of core ideas from the main K-12 science disciplines is thoughtful. Nevertheless there are aspects of emphasis of the design of the Framework as a whole that need more discussion. Among other reasons, it is important for those who will convert these choices—these strong emphases and long arguments—into actionable standards to know why a sympathetic reader of the Framework might have doubts about underlying assumptions and arguments. These doubts have to do with the Framework's Practices, Crosscutting Concepts, and Engineering/Technology Dimensions.

"Practices"

A key chapter of the Framework, perhaps *the* key chapter, rationalizes the choice of principal "Dimensions" of the Framework. Here, too, anthropological, historical, sociological analysis of science is made a key part of K-12 science education. Also, the elevation of engineering to a position equivalent to that of physical, biological, and earth/space science in K-12 education is explained. The authors insist, "Any education that focuses predominantly on the…facts of science—without developing an understanding of *how those facts were established* or that ignores…important applications of science in the world misrepresents science and marginalizes the importance of engineering."[19] [Emphasis ours.] The key concern is about *how science really works*. There is much to admire in that apologia. Still, there are some puzzles for the culturally aware reader as well as some quiet shifts of emphasis that warrant a sigh of relief.

One minor puzzle is about a central question of science study, "…how those facts [of science] were established," that is, how it really works, and "Understanding How Scientists Work."[20] Cited here, among others, as key sources are several books such as those by Latour and Woolgar (1986), Collins and Pinch (1993), and Pickering (1995). These were important in a trendy movement of the 1980s and 90s that went by such names as science studies, STS (sci-tech studies), (new) sociology or anthropology of science, cultural studies, cultural constructivism, and postmodern science. For a time, books like these were widely influential (elsewhere than among scientists) as new and deep insights on *what scientists actually do*. Their main claim on the nature of scientific knowledge was that the "truth" of science is local; that what passes for truth is chiefly the outcome of *negotiations*; that acceptance in science is a matter of networking and power, not correspondence with reality. This was, in effect and despite the variation in names, standard-issue postmodernism.

It was also self-contradictory. They argued: it is true that there is no truth in scientific inquiry, only "truth" (in quotation marks)—that is, agreements on *whose claims count*.[21]

But then, how can *their* own (social-scientific) argument be true and not just "true"? The movement suffered well-deserved setbacks in the late 1990s, with rebuttals from distinguished scholars[22] and from the celebrated "Sokal Hoax," which exposed the remarkable ignorance—of science content and practices—in that branch of science studies.[23] But an early draft of the first NRC-sponsored Science Education Standards declared its adherence to the postmodern view of science. Objections from many knowledgeable scientists caused those words to be dropped from the final (1996) standards, although some postmodernist views remained.[24]

Is it possible that the writers of the new Framework are unaware of that history? The Framework cites, presumably with approval, iconic works that deny, in effect, the 300-year epistemological fundamentals and successes of natural science. Happily, this Framework's science passes on no postmodern attitudinizing. That's the sigh of relief. But we worry about standards-writers and other readers of the Framework. They must be properly concerned to convey *how science works*. Without full explanation, then, citations of literature whose view of how science and scientists work contradicts the intent of the Framework—which is to depict science as reliable and truth-indicative knowledge about nature—is a worry.

Another sigh of relief issues upon a true novelty of this Framework. The centrality, in all its predecessors, of Inquiry (in "inquiry-based learning") is questioned, and in fact set aside. The Framework admits that "…attempts to develop the idea that science should be taught through a process of inquiry have been hampered by the lack of a commonly accepted definition of its constituent elements. Such ambiguity results in widely divergent pedagogic objectives …counterproductive to the goal of common standards." Also, "…Current research in K-12 science classrooms reveals that earlier debates about such dichotomies as 'direct instruction' and 'inquiry' are simplistic, even mistaken, as a characterization of science pedagogy."[25] The authors wisely demote what has long been held the essential condition of K-12 science: "Inquiry-based learning."

But that's not the end of the matter. In this Framework, "inquiry learning" and the learning of "scientific reasoning" morph into more specific *processes*, primarily cognitive skills. They are treated here, as in predecessors, as elements of science content, i.e., as subject matter. Doing so can be innocuous, so long as the processes are taught in direct connection with content as more traditionally defined. (See above, "Doing It Like Scientists.") When treated as separable, distinct, independent elements of science learning, however, the same confusions as before can arise. An example of this can be found in the following section.

Scientific Reasoning

Directly and indirectly, the Framework, like its predecessors, is making (scientific) reasoning a part of content, to be taught per se and learned, for which standards must be set. "Scientific reasoning" is a catch-phrase in current literature on K-12 science, a major part of science "processes." Thus, in 2009, *Science* magazine ran a full-length article on "Learning and Scientific Reasoning," from a nine-author consortium. Lei Bao of the

Ohio State department of physics was the lead author.[26] This fascinating paper included data of high quality: isolated variables, adequate populations, appropriate statistics, and controls.

The subjects were two large, matched cohorts of beginning college students, one American, the other Chinese. All were candidate Physics majors. Described is the conceptually demanding, problem-intensive precollege physics in China and by contrast the far less exhaustive, less conceptually demanding American curriculum. Both cohorts took three available tests. Two (Physics) tests were the Force Concept Inventory (FCI) on mechanics and the Brief Electricity and Magnetism Assessment (BEMA). The third test was the Lawson Classroom Test of Scientific Reasoning (LCTSR), supposed to measure *general* scientific reasoning, including "science processes." Most of the testing was done in 2007— more than ten years after the current styles for standards were adopted in the U.S. The Chinese did extremely well and rather well, respectively, on FCI and BEMA. The Americans did very poorly on both.[27] On the LCTSR—the putative test of (scientific) reasoning—both cohorts produced broadly passing *and essentially indistinguishable* score distributions. The authors are very firm about scientific reasoning: *their claim is that it is taught neither here nor in China*.

But general scientific reasoning (or inquiry, or "processes") *is* taught in the U.S.! In one form or another it has been a defined and distinct part of K-12 science since the appearance of the AAAS *Benchmarks* and even more so after issue of the first national science standards. Yet the American students did no better than the Chinese on the assessment of scientific reasoning while doing far worse on the actual science test. The Chinese learned to solve physics problems—which *is* by any measure reasoning—about physics; the Americans didn't. The Americans study scientific reasoning, explicitly, in school (despite the authors' belief that they don't), but did no better than the Chinese did on what is supposed to be a test of scientific reasoning. So could it be, perhaps, that making at least one distinct, principal "Dimension" of science curriculum be the explicit study of general "scientific reasoning" won't make much difference to the scientific reasoning of students—and, perhaps, insofar as it detracts from or substitutes for the acquisition of actual scientific knowledge, some net harm may be done.

We concede that one example like this cannot be dispositive on the value of distinguishing cognitive skills from knowing the facts, vocabularies, methods, and conclusions of science. But the state of the data does not convince us that the heavy labor of installing process learning per se, as in this framework, is fully justified by the highest standards of evidence. The *processes* of disinterested inquiry differ in detail from one to another field of knowledge; but the fundamentals are the same.[28] They should be inculcated everywhere in the K-12 curriculum. This Framework does move away from the vagueness of "inquiry learning" and other constructivist favorites to the more specific science *processes*. That is a welcome change. But potential confusions remain.

Engineering, etc.

Everyone with experience of both (basic) science and engineering knows, and usually defends, the deep interdependence of these two great disciplines. Characteristics of thought and practice supposed to distinguish them from one another require ever more verbose exposition as each discipline grows. See, for example, the lengthy Box 3-2 of the Framework, "Distinguishing Practices in Science from Those in Engineering."[29] It is prolix and not very convincing.

Box 3-2: Distinguishing Practices in Science from Those in Engineering

1. Asking Questions and Defining Problems Science begins with a question about a phenomenon, such as "Why is the sky blue?" or "What causes cancer?" and seeks to develop theories that can provide explanatory answers to such questions. A basic practice of the scientist is formulating empirically answerable questions about phenomena, establishing what is already known, and determining what questions have yet to be satisfactorily answered.	**Engineering** begins with a problem, need, or desire that suggests an engineering problem that needs to be solved. A societal problem such as reducing the nation's dependence on fossil fuels may engender a variety of engineering problems, such as designing more efficient transportation systems, or alternative power generation devices such as improved solar cells. Engineers ask questions to define the engineering problem, determine criteria for a successful solution, and identify constraints.
2. Developing and Using Models Science often involves the construction and use of a wide variety of models and simulations to help develop explanations about natural phenomena. Models make it possible to go beyond observables and imagine a world not yet seen. Models enable predictions of the form "if . . . then . . . therefore" to be made in order to test hypothetical explanations.	**Engineering** makes use of models and simulations to analyze existing systems so as to see where flaws might occur or to test possible solutions to a new problem. Engineers also call on models of various sorts to test proposed systems and to recognize the strengths and limitations of their designs.
3. Planning and Carrying Out Investigations Scientific Investigation may be conducted in the field or the laboratory. A major practice of scientists is planning and carrying out a systematic investigation, which requires the identification of what is to be recorded and, if applicable, what are to be treated as the dependent and independent variables (control of variables). Observations and data collected from such work are used to test existing theories and explanations or to revise and develop new ones.	**Engineers** use investigation both to gain data essential for specifying design criteria or parameters and to test their designs. Like scientists, engineers must identify relevant variables, decide how they will be measured, and collect data for analysis. Their investigations help them to identify how effective, efficient, and durable their designs may be under a range of conditions.

What, then, is the real justification for elevating Engineering and Technology to the status of the three basic science disciplines for the purpose of K-12 science standards? The key argument is that, while science uses its tools (facts and theory plus *practices*) in search of *explanations* for natural phenomena, engineering—with the same tools and explanations—seeks *designs*.[30] Also, science is focused on the natural-built world, while engineering is concerned with the "human-built" world. All this has some truth in it, and a touch of poetry, though much of the "human-built world" and the operations that build it were here long before what we really mean by "engineering" existed.

Given the meager hours for science in K-12, is this boost for engineering worth the trouble, the distractions, even the poetry? We suspect the presence of institutional or political considerations, and enthusiasm for that E in STEM as the key to national prosperity, beyond purely rational argument. Technology and design *can* be used to enhance the interest of students in science, especially with scientific tools, and to encourage their iterative refinement of practical solutions, as in the laboratory. So the harm done may be small; but it might not be negligible. The *argument* for engineering as a full partner in K-12 science content *matters*: yet as presented here it is weak. Weakness will not enhance respect for the Framework's other arguments, many of which are strong, and important. Respect is needed, from science supervisors and teachers as well as standards-writers. Like a few serious readers, they might ask: "Why not medicine, then? Modern medicine, an applied science like engineering, has *art* in its practice, like engineering; and today both have deep involvement in creating and using basic science."

Crosscutting Concepts

"Patterns," "Cause and Effect: Mechanism and Explanation," "Stability and Change": those are samples of what the Framework calls "Crosscutting Concepts." The value of using them is argued strongly[31] but it is nevertheless hypothetical. The authors seem confident, at first, that their Crosscutting Concepts "…help students develop a cumulative, coherent, and usable understanding of science and engineering." But, as already noted, the Framework admits a few lines further on that research on learning and teaching the crosscutting concepts is "limited" (i.e., inadequate). That sounds to us like a reason for caution. Yet the Crosscutting Concepts are made one of the six principal Dimensions of the Framework (see the Table of Contents, above). Nothing tentative about that. These "concepts," mind you, are *abstractions*. They are universals, certainly not unique to science. "Patterns" applies to almost anything with moveable parts or to any system of thought. "Systems and system models" is equally general. "Stability and Change" is as representative of government, politics, the history of art, or the technique of pole-vaulting as it is of science.

The Framework admits that there isn't much difference between its Crosscutting Concepts and the "unifying concepts" or "common themes" of most predecessor standards. The devil is entirely in the choice of words. Discussion of these themes in the Framework is articulate. Nevertheless, they are very high-level constructs, whose real significance may be grasped by able and relatively mature pre-collegiate students but not by many others, even in the final years of high school. Inserting them sooner than most students are ready for such abstract generalization is what these authors are trying *elsewhere* to avoid, as with the "Boundary Statements."

Accessories

By "accessories," we mean those "broader, less science-substantive" issues referred to in the Introduction. Among them are some bodies of mostly well-written advice that give us pause. We visualize teams of standards-writers toiling to turn this large Framework into a set of ("limited") science standards that can realize in student performance all or even most of the advisories. This will prove difficult if not impossible. The Equity and Diversity chapter (11) is a case in point. It begins where the Framework does: by stating that standards must reflect high academic expectations for all students. A platitude today, yes, albeit a noble one that it is practically obligatory to reiterate. In effect, it asserts that all students can learn serious (rigorous) science and engineering. It then defines *equity* and *inequity* by a generous selection from among the multiple meanings assigned to those words, in common discourse and in education. The emphasis here, however, is on just one inequity: the infamous "gap" in achievement of some minority student populations as against the majority.

There follows a protracted list of known (or conjectured) sources of *that* inequity. For example: differential quality of schools, equipment, and teachers; inadequate prior preparation of the affected students in other subjects, or in the home, in early childhood; or low learning expectations on the part of teachers, of family, biases of various kinds. Added thereto is what is seen as a general blemish on education: that school and curriculum fail to make instruction "inclusive and motivating for diverse student populations."

This chapter focuses on correction of just one of the many putative factors of the inequity—lack of "inclusiveness." The proposed correction, however, means in practice not only different pedagogical styles but also different subject matter for affected students. The goal is to "equalize opportunities to learn," presumably by modifying content for all, or by modifying it just for the subpopulation affected by lack of inclusiveness—enabling them thereby to achieve equitably. As the Framework notes, "Tailored instructional perspectives and additional approaches…may be needed to engage these and other students in the full range of practices described in chapter 4."[32] We are urged to teach differently to different students, or to teach different or modified subject matter to all, in aid of removing a defined inequity.

Yet trying to do that means abandoning a repeatedly announced goal: to have one optimum set of science standards that applies to all students. The modifications discussed imply changes in standards or at least changes of emphasis within or among particular standards. The proposal is therefore in effect to make big changes to one possible cause of inequity in learning yet *without any sound basis for estimating the quantitative importance of that cause*. But: if an ill effect is known or claimed to have a large number of causes, and the fractional contribution of each cause to the total ill effect is unknown, then to attempt elimination of the ill effect by an unproven effort to remove *just one* of the causes is…well, not the best strategy. The probability of measurable success is small, and the burden on teachers coping with already demanding standards is great.

We think, again, of those standards-writers, who are being asked to arrange things in their work so that we can have it both ways: uniform and uniformly rigorous expectations of student performance *and* non-uniform teaching and content choices, *or* offering the entire population content designed for a sub-population. It is an added ambiguity, a departure from clarity and specificity of the Framework. Accessories like this cause confusion because they aren't really focused on standards. They are focused on other societal challenges and objectives—honorable ones, to be sure.

Summary and Conclusion

This Framework is important; it will be useful; parts of it epitomize good writing and sincerity, as well as scientific intelligence. It is an improvement on its national predecessors, albeit an evolution from them, not a revolution. In those parts of the Framework that are of primary concern—choices of, and explanations for, eventual standards of student performance on science content, the Framework matches or exceeds in quality what we have in current offerings from the national and international testing agencies. Moreover, this new offering is, in our opinion, as good on content and rigor as some of the top-rated state standards reviewed by us. On a scale of seven points for "Content and Rigor," we should assign the seven (see Appendix I for the common grading metric).

As to "Clarity and Specificity," however, we encounter some difficulty. For clarity of *writing*, and the organization of those chapters and sections directly concerned with science, we have admiration. Moreover, the organization of that material, which has been everywhere a problem the last two decades, is probably as clear as so intricate an exposition can be. Yet potential confusions remain for standards-writers and users of standards, due to the sometimes-elusive proposals for integration of science and engineering *processes* with core disciplinary science *knowledge.* On balance, this document is not exactly what it is announced to be: a framework for new K-12 science education standards. It is, in fact, much more than that—and the additions and extras may over-complicate, confuse, and possibly mislead readers and users. Some of the extras, beyond obscuring what is announced as the Framework's purpose, lack the taut specificity that such a document should have in order for the standards based upon it to be taut and specific. That lack can confuse or distract standards-writers and teachers. Much of what comes in the accessories is interesting, socially positive, and possibly important beyond science standards; but not much of it would be helpful in a crisp, executable proposal for making standards (and curriculum). On a scale of three for "Clarity and Specificity," a one seems about right.

That makes a total of eight points out of a possible ten. On the current Fordham conversion rubric, that amounts to the letter grade B-plus. If the statue within this sizable block of marble were more deftly hewn, an A grade would be within reach—and may yet be for the standards-writers, so long as their chisels are sharp and their arms strong.

Endnotes

[1] Daniel T. Willingham, *Why Don't Students Like School?* (San Francisco, CA: Jossey-Bass, 2009), 37.
[2] Committee on Conceptual Framework for the New K-12 Science Education Standards, *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (Washington, D.C.: National Academies Press, 2011), 10-1.
[3] Ibid., 11-1.
[4] Ibid., 13-1.
[5] Ibid., 4-1; All the above is supported with exhaustive citation, including in all NRC predecessors to this Framework, notably its *National Science Education Standards* (1996), and other semi-official advisories, including those from Project 2061 of the American Association for the Advancement of Science and from the National Science Teachers Association.
[6] Currently, Achieve, Inc. is developing a set of "next generation" science standards based off of this Framework. See http://www.achieve.org/next-generation-science-standards for more information.
[7] Often, until recently, grouped under "Inquiry" or "Scientific Inquiry."
[8] *Framework*, vii.
[9] *Framework*, 1-1, ES-2.
[10] For more, see Fordham's published reviews of state science standards from 1998 (*State Science Standards*) and 2005 (*The State of State Science Standards*), both available at www.edexcellence.net. Note also Fordham's *The State of State Science Standards in 2011*, forthcoming, November 2011.
[11] James B. Conant, *Science and Common Sense* (New Haven, CT: Yale University Press, 1951).
[12] *Framework*, ES-1; the shortcomings of current science education in the United States are due, according to this Framework, to (among other things) "…failure to provide students with engaging opportunities to experience how science is actually done." But it is very unlikely that students, at least in the primary grades, *can* experience "how science is actually done." It is a firm finding of cognitive science that *experts*—composers or concert pianists or judges, as well as working physicists—think quite differently about their work than do novices.
[13] Willingham, 22.
[14] For an example, see: M.J. Dougherty, C. Pleasants, L. Solow, A. Wong, and H. Zhang, "A Comprehensive Analysis of High School Genetics Standards: Are States Keeping Pace with Modern Genetics?," *Journal of Life Sciences Education* 10 (Fall 2011), http://www.lifescied.org/content/10/3/318.full.pdf+html (accessed September 16, 2011).
[15] Dougherty, 5-25.
[16] Ibid., 9-5 ff.
[17] Ibid., 9-9.
[18] See, for example: Ze'ev Wurman, "Education to Raise Technology Consumers instead of Technology Creators," *Monolith IC3D Blog*, August 4, 2011, http://www.monolithic3d.com/2/post/2011/8/education-to-raise-technology-consumers-instead-of-technology-creators.html (accessed September 16, 2011).
[19] *Framework*, 3-2.
[20] Ibid.
[21] Paul R. Gross, *Politicizing Science Education* (Washington, D.C.: Fordham Foundation, 2000).
[22] See, for one book-length collection of scholarly essays, Noretta Koertge, ed., *A House Built on Sand: Exposing Postmodernist Myths about Science* (New York: Oxford University Press, 1998).
[23] As a test of the charges of scientific ignorance among postmodernist and cultural-studies critics of science, physicist Alan Sokal submitted to a leading cultural studies journal an essay on physics, in excellent postmodern-feminist-multicultural style but filled with gross errors in basic physics and mathematics. It was accepted and published. The hoax was then revealed by Sokal in an early issue of *Lingua Franca*. See, for example, one almost-contemporary report on the Sokal Hoax: Paul A. Boghossian, "What the Sokal Hoax Ought to Teach Us: The Pernicious Consequences and Internal Contradictions of 'Postmodernist' Relativism," *Times Literary Supplement*, December 13, 1996, 14-15.
[24] Gerald Holton, "Science Education and the Sense of Self," in *The Flight From Science and Reason*, ed. P.R. Gross, N. Levitt, and M. W. Lewis (New York: New York Academy of Science, 1996).
[25] *Framework*, 3-2, 10-9.
[26] Lei Bao et al., "Learning and Scientific Reasoning," *Science* 323, no. 5914 (2009): 586-87.
[27] A fuller and documented account can be found in Paul R. Gross, "Learning Science—With Reason," *American Educator* 33, no. 1 (2009): 35-40.
[28] See, for example: Susan Haack, *Defending Science—Within Reason: Between Scientism and Cynicism* (Amherst, NY: Prometheus Books, 2003).
[29] *Framework*, 3-29 ff.
[30] Ibid., 3-15.
[31] Ibid., 4-2.
[32] Ibid., 11-5.

Appendix I
Common Grading Metric

The review of this Framework compared its content to a set of subject-specific expectations (see Appendix II). Based on that comparison, we assigned the Framework two scores, one for "content and rigor" and one for "clarity and specificity." Content and rigor is scored on a scale of 0 to 7 points, while clarity and specificity is scored on a scale of 0 to 3 points, as follows.

Content and Rigor

7 points – Standards meet all the following criteria:

- Standards are reasonably comprehensive in terms of content. (For criteria of science content coverage and expectations, see Appendix II.) Coverage for each of the three core scientific disciplines is adequate, and good decisions have been made about what topics to include under each heading.

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

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

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

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

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

6 points – Standards fall short in one of the following ways:

- Some important content (as identified, for example, in our content criteria) is missing.
- Content is covered satisfactorily but the presentation is not of uniformly high quality.
- Some proposed content in the standards is unnecessary and distracting.
- Standards do not always differentiate between more and less important content (i.e., importance is neither articulated explicitly nor conveyed via the number of standards dedicated to a particular topic). In other words, these standards overemphasize a few topics of little importance or underemphasize a few topics of great importance.
- Some of the expectations at particular grade levels are set unrealistically high or too low.
- There are small problems or errors in the presentation of important subjects, such as those listed among our content criteria.

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

- Some important content (as identified, for example, in our content criteria) is missing.
- Content is covered satisfactorily but the presentation is not of uniformly high quality.
- Some proposed content in the standards is unnecessary and distracting.
- Standards do not always differentiate between more and less important content (i.e., importance is neither articulated explicitly nor conveyed via the number of standards dedicated to a particular topic). In other words, these standards overemphasize a few topics of little importance or underemphasize a few topics of great importance.
- Some of the expectations at particular grade levels are set unrealistically high or too low.
- There are a few problems or errors in the presentation of important subjects, such as those listed among our content criteria.

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

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

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

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

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

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

2 points – Standards fall short in one of the following ways:

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

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

1 point – Standards fall short in both of the following ways:

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

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

0 points – Standards fall short in the following way:

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

Clarity and Specificity

3 points – Standards are clear, coherent, and well organized.

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

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

2 points – The standards are somewhat lacking in clarity, coherence, or organization.

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

1 point – The standards fail frequently to be clear, coherent, or well organized.

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

0 points – The standards are incoherent and/or disorganized.

They will not be helpful to users. They are sorely lacking in detail. Scope and sequence are a mystery.

Final Grades

A final grade for each set of standards is calculated by adding the “Content and Rigor” score to the “Clarity and Specificity” score. Grading is on a 10-point scale, as defined below.

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

Appendix II
Criteria for Science Content: Coverage and Expectations

Note that these criteria were developed by a team of science experts to evaluate K-12 science content *standards*. While we used these criteria as a guide for analysis and scoring of this Framework, it is important to note that the Framework is not itself a standards document; it is instead meant to inform standards.

Introduction

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

1. 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.

2. 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.

3. Earth/Space Sciences

- 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.

Science Content: General Expectations for Learning through Grade Twelve

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 twelfth-grade 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.

1. Physics

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

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

2. 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.

3. 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.

4. 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.

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

1. 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.

2. 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.