The Preparation of Physics Teachers and the Next Generation Science Standards in the United States

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Abstract

In the United States, individual states establish their own state science standards that guide school instruction. In March of 2013, the Next Generation Science Standards (NGSS) were released after more than two years of development with the participation of several states. Twenty-six states have indicated that they would adopt these standards as their state standards over the next few years. Such a wide-scale adoption of a common set of science education standards will be a major milestone in US science education. It will also have an enormous impact on US physics education, teacher preparation, and the agencies and programs that fund science teacher preparation, such as the National Science Foundation Noyce Program. In this presentation we will discuss the structure of the NGSS and examine a variety of issues that have significant implications for the preparation of future physics teachers. Among the issues are the inclusion of scientific and engineering practices and crosscutting concepts, engineering as a discipline within the NGSS, the emphasis on fields, and the possible inclusion of significant amounts of Earth and Space Science content in physics courses. These developments are likely to influence other countries contemplating a more holistic view of science education.

Keywords: standards, teacher preparation, physics education

US education: The Primacy of States and Local Control

Elementary and secondary education in the United States is delivered through a complex system of 98,817 public elementary and secondary schools that in 2011 served 49.4 million students, along with 33,366 private schools that in 2011 served 5.3 million students [1]. Public schools are managed by 17,011 local education agencies (LEAs) that vary enormously in size and composition [2]. The LEAs themselves are governed by locally-elected school boards. The LEAs have considerable autonomy to determine instruction, but they are guided by state policy.

Individual states specify a range of educational requirements through legislation, including the number and kind of courses required for high school graduation, what instructional materials may be purchased by schools, standards for teacher preparation and licensing, standards for learning, and the testing of students to determine how well they have met those standards. These requirements vary significantly from state to state, and LEAs can have considerable flexibility within those requirements. The Federal government, on the other hand, plays only a minor role in U.S. education and accounts for only 8.3% of total spending on publicly funded elementary and secondary education [3]. Thus the control of education policy in the U.S. is at the state level.

In the 1990s there was an attempt to bring more uniformity to science education standards in the states, as part of a broader effort in science education reform [4]. Two non-governmental scientific organizations that broadly represent the U.S. scientific community, the American Association for the Advancement of Science (AAAS) and the National Academy of Sciences (NAS), produced a series of documents to help guide the development of state science standards. These documents [e.g. 5,6,7] outlined what a scientifically literate citizen should know and at what point in schooling students should learn these concepts. However, those documents were not intended to be directly adopted by states. Instead, individual states used them (to greater or lesser degree) as guides in the development of their own state standards.

The Next Generation Standards Movement

Some twenty years after the beginning of the standards movement, the National Governors Association (NGA), an organization founded in 1908 by the governors of the states [8], decided that states should collaborate more and produce common education standards that would be adopted by most states. The first fruit of this effort was a set of standards for English language arts and another set of standards for mathematics known as the Common Core standards [9].

Science was not far behind, but unlike the Common Core, the development effort was not led directly by the NGA. Instead, the National Academy of Sciences was tasked to create a document that identified what was important in science and engineering that all students should know, and when they should learn these things. In 2010, the National Research Council (the operating agency of the NAS) formed a committee that was chaired by Dr. Helen Quinn, a distinguished theoretical physicist and a former president of the American Physical Society. Other members included distinguished scientists (including two Nobel laureates), educators, and experts in cognitive science. The document they produced would be then be turned into a standards document that individual states could adopt through their normal legislative procedures.

The Framework

The NRC committee produced a report titled *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* [10] that was released in July 2011 after extensive review by scientists, educators, and a variety of organizations and professional societies. This document has three dimensions, as indicated by the title. It also incorporates engineering as distinct from science, both in the practices and in the content.

The first of these dimensions, the scientific and engineering practices, are those behaviors that are at the core of what is meant by engaging in science and engineering. These practices are found in all fields of science and engineering, and they are enumerated here:

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.

Practices 1 and 6 have somewhat different interpretations for science versus engineering, reflecting the differences between the disciplines. While engineers might ask scientific questions, their focus is defining a problem and designing a solution to that problem. Scientists may also design solution to a problem (such as when space scientists design scientific instruments that minimize mass and power requirements). But such design solutions are steps along the way to answering scientific questions, not end goals in and of themselves. The practices can be seen as the behaviours that make up "scientific inquiry", which the previous standards documents stressed as the way to learn science [6,7].

The second dimension in the *Framework* is the notion of a crosscutting concept. The crosscutting concepts are found in all aspects of science and engineering, and the authors of the *Framework* wanted to emphasize the unity of science by viewing science through this lens. Moreover, research in cognitive science indicates that expertise in science is grounded in the development of coherent conceptual frameworks around topics. For example, novice physics students will organize problems by surface features, such as the presence of an inclined plane, while experts organize problems through principles such as conservation of energy [11]. Thus an emphasis on crosscutting concepts could help students develop more expert-like scientific thinking.

The crosscutting concepts are:

- Patterns.
- Cause and effect: Mechanism and explanation.
- Scale, proportion and quantity.
- Systems and system models.
- Energy and matter: Flows, cycles, and conservation.
- Structure and function.
- Stability and change.

One of the crosscutting concepts, energy, is also a disciplinary core idea in the physical sciences. However the concept of energy as an organizing principle extends through all of science and engineering.

The third dimension of the *Framework* is the content, the Disciplinary Core Ideas (DCIs). This is what people usually think about as "science", though the *Framework* argues that without the other two dimensions one does not have an adequate or realistic depiction of science and engineering. The DCIs are divided by discipline:

1) Physical Science.

2) Life Science.

3) Earth and Space Science.

4) Engineering, Technology, and Applications of Science.

A narrative for each of these major divisions outlines the big ideas for each topic. For example, in Physical Science (PS), topic 2 is titled "Motion and Stability: Forces and Interactions." This topic is further subdivided into sections such as "PS2.A: FORCES AND MOTION." The *Framework* discusses learning progressions throughout the document and it organizes the content along these lines. For each section of the DCIs (such as PS2.A), a set of grade-band endpoints are specified, outlining what a student should be able to know and do as a result of instruction at the end of that grade-band. The *Framework* also discusses other topics, such as integrating the three dimensions. However, the *Framework* by itself is not a document that states could adopt to guide instruction. That set of documents, known as the Next Generation Science Standards (because they are a generation removed from the first set of U.S. science standards), would be developed next, using the *Framework* as the guide.

The Next Generation Science Standards

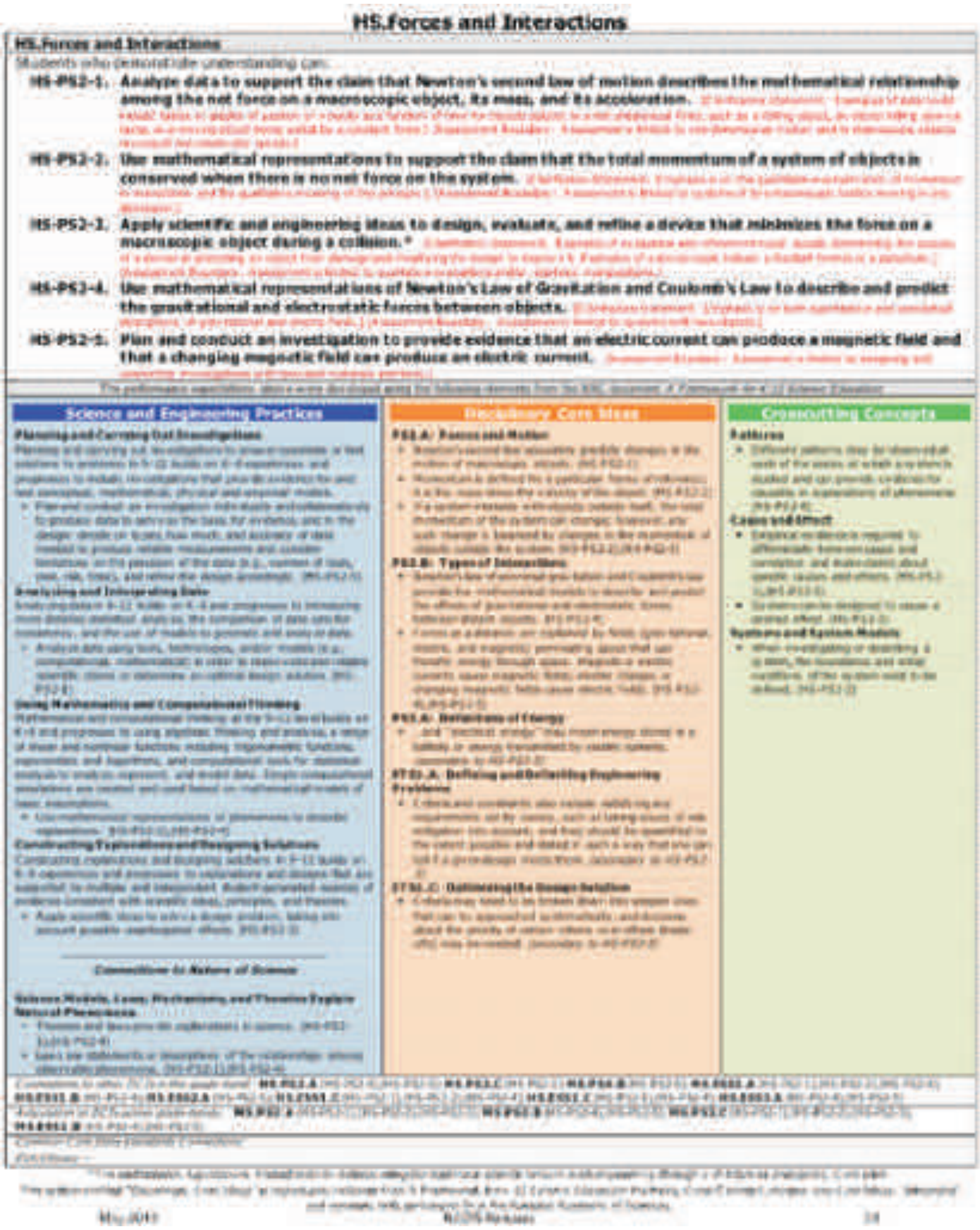
The development of the Next Generation Science Standards (NGSS) was led by Achieve, which is a non-profit organization founded in 1996 by governors and business leaders to help states improve education [12]. Achieve established a collaboration with the 26 lead state partners, states that committed early on to eventually adopting the NGSS as their state standards. The AAAS and the National Science Teachers Association (NSTA) also joined the partnership.

A writing team of 41 scientists, science educators, teachers, and state leaders was formed, with a leadership committee of 9 (including the lead author of this paper). These individuals were nominated by organizations including AAAS, NSTA, and the NAS, as well as by state leadership groups. Several members of the *Framework* committee were also included on the writing team. Over the next two years the writing team produced the NGSS [13]. Extensive feedback was provided to the writing team by the lead state partners, AAAS, NSTA, and many others throughout the process, which included several private and public releases of drafts of the NGSS.

One the first decisions to be made concerned the architecture of the NGSS. The purpose of the standards is not to directly guide instruction, but to guide the assessment of students. Thus it was determined that the NGSS would be written as a set of performance expectations (PEs) for students – things that students should be able to do as a result of instruction. Each performance expectation needed to combine the Practices and Crosscutting Concepts with the Disciplinary Core Ideas in a way that student understanding all three dimensions could be assessed. For elementary grades, the PEs were grouped by grade level, from Kindergarten through 5th grade. For secondary school, the PEs were grouped by grade band: Middle School and High School. The PEs can be organized by DCI (so, for example, all of the High School PS2.A content can be placed in one document) or by a topical arrangement (for example, High School: Forces and Interactions). These decisions were made to accommodate as best as possible the different state legislative requirements for their standards.

An example of a portion of the NGSS, arranged by topic, is presented in Figure 1. The upper box contains the PEs. Each PE addresses selected, related DCIs (the text of which is taken from the *Framework* grade-band endpoints), one Practice, and one Crosscutting Concept. It is critical to understand that the PEs are guides to assessment, not guides to instruction. Thus while HS-PS2-1 points the assessment toward the practice *Analyzing and interpreting data*, it is expected that students will be doing additional things, such as designing and conducting investigations that would provide them with the data they are to analyze. Each PE also has some clarifying statements and assessment boundaries (if needed), appended in red. Assessment boundaries are always written as negative statements indicating what information exceeds the standard that all students are expected to meet. Some PEs are marked with an asterisk (*). Those PEs integrate engineering content.

The middle boxes show the three dimensions of the *Framework* that are addressed by the PEs above, with each PE coded to the corresponding DCIs, Practice, and Crosscutting Concept that it assesses. The bottom box presents connections: How the topic contributes to topics within that grade band, what prior topics contribute to the topic, what the topic contributes to later topics, and what connections exist to the Common Core Standards. The connections to the Common Core Standards have being added and were not present in the document as released in May, 2013.


HS.Forces and Interactions

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

HS-PS2-2. Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system.

HS-PS2-3. Apply scientific and engineering ideas to design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision.*

HS-PS2-4. Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.

HS-PS2-5. Plan and conduct an investigation to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current.

Science and Engineering Practices

Disciplinary Core Ideas

Crosscutting Concepts

Figure 1. A sample of the NGSS from High School Physical Science, organized by topic

Challenges and Implications for Physics Teacher Preparation

The NGSS present many challenges to the states that will adopt them. One critical issue to understand is that the PEs are a guide to assessment, not a directive for instruction. And each PE is intended to guide assessment of student understanding of all three dimensions of the *Framework*. This integration of the dimensions will be a big challenge to all teachers since they are not used to thinking explicitly along these lines. Even those teachers who were using an approach of teaching science by doing science (thus utilizing the Practices in instruction) will still initially have difficulty understanding how to weave in the Crosscutting Concepts. Energy is both a DCI and a Crosscutting Concept, and physics teachers will need to know how to teach about energy as such and also know how to use the concept of energy as a unifying theme across physics instruction.

A second issue is the distinction between science and engineering. Engineering takes a much more prominent role in the *Framework* than in previous documents of this type, and the NGSS reflect this emphasis. While engineering content is distributed throughout the NGSS, physics is a particularly good area in which to embed engineering. The PE HS-PS2-3 in Figure 1 is an example of this. In fact, High School Physical Science has five PEs that are tagged as engineering PEs, while Life Science and Earth and Space Science have only two each. So physics teachers will be responsible for a large fraction of engineering content in High School and they will have to become much more familiar with the engineering design process.

A third issue is that the NGSS contain much more Earth and Space Science content than is now typically taught in schools at all grade levels. Where is this Earth and Space Science content going to go? Some states still require a minimum of only 2 years of science to graduate from High School. That will have to change because it is impossible to accomplish the goals of the NGSS without at least 3 years of science classes. Furthermore, many schools will want to offer additional, higher-level courses that can sometimes be counted for college credit (as they do now). So it is likely that in most NGSS states there will be three basic science courses taken by all students (with additional advanced science courses for students who want them), and that the ESS content will be distributed across Physics, Chemistry, and Biology. Actually, many Space Science topics lend themselves well to inclusion in physics, such as HS-ESS1-1, given below (note that the assessment boundary puts a limit on the kind of content that can be assessed).

HS-ESS1-1. Develop a model based on evidence to illustrate the life span of the sun and the role of nuclear fusion in the sun's core to release energy that eventually reaches Earth in the form of radiation. [Clarification Statement: Emphasis is on the energy transfer mechanisms that allow energy from nuclear fusion in the sun's core to reach Earth. Examples of evidence for the model include observations of the masses and lifetimes of other stars, as well as the ways that the sun's radiation varies due to sudden solar flares ("space weather"), the 11-year sunspot cycle, and non-cyclic variations over centuries]. [Assessment Boundary: Assessment does not include details of the atomic and sub-atomic processes involved with the sun's nuclear fusion].

Another ESS PE that would readily be included in physics is: **HS-ESS1-4: Use mathematical or computational representations to predict the motion of orbiting objects in the solar system.** However, many physics teachers might not have taken an astronomy course and might not be very familiar with Kepler's Laws, or they might be unfamiliar with the sunspot cycle or space weather. There are other topics in Earth and Space Science that are even further from typical physics content that could find their home in a "physics" course. Thus professional development and teacher preparation programs will have to provide additional scientific and pedagogical content knowledge on these topics so that physics teachers are able to teach them effectively.

A final challenge to consider here is the issue of fields. The *Framework* puts considerable emphasis on the reality of fields, especially in forces and conservation of energy. Beginning in 4th grade, students learn that objects can exert forces on each other without touching. In Middle School, students explore action at a distance and identify the thing that exerts the force, the field, as a real entity. In High School, the principle of conservation of energy includes the field energy (at a rudimentary level) as a means of explaining everyday phenomena, as well as invisible phenomena such as chemical bonds. This new emphasis on fields will not be familiar to physics teachers. Conceptually, this may be one of the most challenging additions to the science content in the NGSS. Teacher preparation and professional development programs will have to address this issue, and it may also require some rethinking of the standard undergraduate physics curriculum to provide future teachers with the conceptual knowledge of fields that they need.

Conclusions

The *Framework* and the NGSS represent a significant change in U.S. science education. For the first time, many states will have a common set of science standards based on the latest research on learning and a consensus of what science and engineering knowledge all students should learn. Originally, 26 states pledged to implement the NGSS, a process that takes time since it involves legislation. As of February 2014, eight states (including California) had adopted the NGSS, which represents very rapid progress, and more states will be adopting the NGSS in the years to come. Because the *Framework* and the NGSS contain much that is new, this widespread adoption presents real challenges to current and future physics teachers.

Physics teachers will require much more knowledge about the nature of engineering, a broad view of science that allows them to see how material can be organized by crosscutting concepts, and an understanding of the clear and explicit use of the scientific and engineering practices in instruction. Physics teachers in states that adopt NGSS are likely to be responsible for teaching a considerable amount of Earth and Space Science content that they do not currently teach and which most did not study in school. They will also need to gain a much deeper understanding of fields (a generally unfamiliar concept).

In the U.S., the National Science Foundation funds activity and research in science teacher preparation through the Noyce Program [14]. There are also innovative science teacher preparation programs like UTeach [15] and PhysTEC [16] that are serving as national, replicable models, and professional societies like the American Association of Physics Teachers [17] that will be responding to these challenges. It is likely that over the next few years these programs will develop effective models for physics teacher preparation that are aligned with the NGSS. Furthermore, it would not be surprising if the national standards in other countries are influenced by the NGSS, and that the models developed in the U.S. to deal with the challenges of physics teacher preparation have a commensurate influence.

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