Achieve

Report

International Science Benchmarking Report

Taking the Lead in Science Education: Forging Next-Generation Science Standards

September 2010

INTERNATIONAL SCIENCE BENCHMARKING REPORT

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Forging Next-Generation Science Standards

EXECUTIVE SUMMARY

U.S. students have consistently lagged behind their peers in other nations on international science assessments – a performance increasingly at odds with the challenge of being able to live and compete in a global environment, powered by innovations in science, engineering and technology. A strong foundation in science is clearly critical if today's students are to have the option of pursuing careers in STEM-related fields where employment opportunities are expanding. But the ability to compete in a world economy is not the only issue. More than ever, participating as an informed citizen in a democracy, and making personal decisions, requires the ability to digest current events and make judgments based upon scientific evidence. National efforts in science education are focusing on two key issues: scientific literacy for all students and STEM preparedness to increase the STEM pipeline. From a standards and learning progression perspective, these issues exist on a continuum and are not mutually exclusive. A sound foundation to scientific literacy allows students to pursue Upper Secondary and post-secondary options based on their interests and occupational goals**.**

In response to concerns over the need for a scientifically literate workforce, increasing the STEM pipeline, and aging science standards documents, the scientific and science education communities are embarking on the development of a new conceptual framework for science, led by the National Research Council (NRC), and aligned next generation science standards, led by Achieve. The American Association for the Advancement of Science (AAAS) and the National Science Teachers Association (NSTA) are also key partners in this effort.

Leaders have called for U.S. standards to be internationally benchmarked – reflective of the expectations that other leading nations have set for their students. To that end, Achieve examined 10 sets of international standards with the intent of informing the development of both the conceptual framework and new U.S. science standards. Achieve selected countries based on their strong performance on international assessments and/or their economic, political, or cultural importance to the United States.

All of the countries selected require their students to learn science from Primary through Lower Secondary, which ends at either grade 9 (three countries) or grade 10 (seven countries). In Upper Secondary, countries expect students to pursue further science study by taking courses in biology, chemistry, physics and/or (where available) Earth and space science. The way in which countries structure their standards prompted researchers to think about findings from three perspectives that framed the analysis:

1. SCIENCE THROUGH LOWER SECONDARY SCHOOL: *WHAT KNOWLEDGE AND SKILLS DO COUNTRIES EXPECT ALL STUDENTS TO LEARN IN PRIMARY THROUGH LOWER SECONDARY GRADES PRIOR TO TAKING DISCIPLINE-SPECIFIC HIGH SCHOOL COURSES IN SCIENCE?*
2. UPPER SECONDARY SCIENCE: *WHAT KNOWLEDGE AND SKILLS DO COUNTRIES EXPECT STUDENTS TO LEARN IN UPPER SECONDARY COURSES IN BIOLOGY, CHEMISTRY, PHYSICS, AND EARTH AND SPACE SCIENCE THAT PREPARE THEM FOR POSTSECONDARY STUDY IN SCIENCE, ENGINEERING AND TECHNOLOGY?*
3. EXEMPLARS: *WHAT ARE EXEMPLARY FEATURES OF THE STANDARDS REVIEWED IN THIS STUDY THAT SHOULD BE CONSIDERED BY DEVELOPERS OF NEXT-GENERATION SCIENCE STANDARDS IN THE UNITED STATES? WHAT ARE COMMON SHORTCOMINGS – AND HOW MIGHT THEY BE OVERCOME?*

Achieve's study was limited by design to standards. It did not take into account the broader country context, i.e., how the education system functions as a whole and differences in economic, social, and cultural norms. Where one country may have several standards dedicated to a topic or concept, the actual instructional time may be less than the expectation of another country that had few standards, but required more dedicated instructional time. Other limitations were a dearth of information on student course-taking patterns and pathways that limited Achieve's ability to have an "all students" versus a "stem-capable" view, and the availability of adequate English translations. In addition, the overall coherence of the education system (e.g., teacher education and development, assessments, instructional tools, and supplementary curriculum materials) was not taken into account which creates an incomplete picture. These are all areas for future study.

Achieve's analysis has both a quantitative and qualitative component. The quantitative analysis identifies the specific content and performance expectations the ten high-performing countries have established for each science discipline for Primary through Lower Secondary and for Upper Secondary (subject-specific courses). The qualitative examination complements the quantitative analysis by identifying noteworthy practices and weaknesses among the countries' standards. The table below shows the countries selected for the study and how their standards were analyzed.

Country	Preliminary Qualitative Review	In-Depth Qualitative Review		Quantitative Analysis
		Biology, Chemistry & Physics	Earth and Space Science	
Canada [Ontario]	✓	✓	✓	✓
Chinese Taipei	✓		✓	✓
England	✓	✓		✓
Finland	✓			✓
Hong Kong	✓	✓		✓
Hungary	✓			✓
Ireland	✓			✓
Japan	✓	✓	✓	✓
Singapore	✓	✓		✓
South Korea	✓			✓

Major Findings of the International Benchmarking Study

The overall goal of Achieve's study on international standards is to inform the development of the NRC framework and next-generation science standards. Through a quantitative analysis of international standards, Achieve's reviewers discovered four key findings.

Finding #1 - All countries require participation in integrated science instruction through Lower Secondary and seven of 10 countries continue that instruction through Grade 10, providing a strong foundation in scientific literacy.

Finding #2 –Physical science content standards (physics and chemistry content taken together) receive far more attention in lower primary through lower secondary. Other countries dedicate the greatest proportion of their standards to biology and physics content and the least to Earth and space science.

Finding #3 – Other countries' standards focus life science instruction strongly on human biology, and relationships among living things in a way that highlights the personal and social significance of life science for students and citizens. However, in the U.S., virtually all states also have a requirement for health and physical education from lower primary to lower secondary which could explain the difference in focus.

Finding #4 – Cross-cutting content common to all of the sciences such as the nature of science, nature of technology and engineering receives considerable attention. Inquiry skills in Primary are stressed more than in Lower Secondary. However, advanced inquiry skills receive increasing attention in Lower Secondary.

<u>Exemplary Features</u>

Achieve charged its reviewers to qualitatively review five countries' standards documents to determine exemplary features. Achieve's reviewers submitted six exemplary features for the Conceptual Framework for Science Education committee to consider.

Feature #1 – Standards based around "unifying ideas" for Primary through Lower Secondary seem to confer more benefits than a discipline-based structure. Achieve's reviewers found that developing standards around unifying ideas provided greater coherence and focus within the standards. In addition, this structure provides a more focused perspective in development by providing a method to determine what content should be included.

Feature #2 – Providing multiple examples of performance into content and performance standards makes expectations for student performances specific and transparent. Achieve's reviewers found Canada's use of multiple examples within their standards an excellent method to communicate the level of rigor expected from students. Multiple examples help learners connect concepts with applications in the real world, help them to explain everyday phenomena, and enhance the clarity and accessibility of standards. Incorporating multiple examples (rather than relying on a single example) is important because multiple examples show a range of applications, rather than a single point that can quickly become a limiting factor.

Feature #3 – Making meaningful connections to assessment helps to focus attention on the ultimate goal of raising student achievement. Achieve found three countries, Canada, England, and Hong Kong, make a special effort to show how their standards and assessments are aligned. While the approaches vary considerably, all three countries make solid links between the content they expect students to learn and how that learning will be evaluated. States, districts, and teachers would benefit greatly from understanding the connections and performance expectations required by the statewide assessment.

Feature #4 – Organization and format has an enormous effect on the clarity and accessibility of a country's standards. Achieve found Canada, Singapore, and Hong Kong have user-friendly standards, and their approaches are similar. England's standards are structured differently but are also accessible. Great care was taken on the part of these countries to ensure they were clear and communicated the level of rigor and intent of the standards.

Feature #5 – Developing students' ability to use inquiry, engineering design, and modeling supports student participation in structured projects that nurture scientific habits of mind and stimulates student interest. Developing students' capacity to understand, design and apply physical, conceptual, and mathematical models is a key ability that should be interwoven in the standards. Achieve found that Canada's parallel development of inquiry and design stands out as a quality example. It makes fundamental connections between conducting investigations in the natural world and problem solving in the designed world. It describes a progression of performances from beginning to proficient in four key areas for both inquiry and design: Initiating and Planning; Performing, and Recording; Analyzing and Interpreting; Communicating.

Feature #6 – All student populations should have accessibility to science and guidance should be provided to support this philosophy. Achieve's reviewers found countries who had clearly made accessibility of science to all populations a priority. For instance, England includes guidelines for teaching science to all students that are an important part of a standards document. Hong Kong also includes curriculum adaptations for a diversity of learners including accelerated learners.

Shortcomings

Clearly, the five countries' standards have much to recommend them. However, Achieve also found weaknesses in several areas as described below. These present opportunities for the developers of the NRC framework and new science standards to carve out a fresh vision for science education.

- *Incorporation of Mathematics*: The importance of integrating mathematics with science standards has long been raised as a central issue by both AAAS and the NRC. Recent research has revealed, "*High-school mathematics carries significant cross-subject benefit (e.g., students who take high-school calculus average better grades in college science than those who stop at pre-calculus).*"[1] This is an area in which none of the countries has been completely successful.
- *Evidence-based Inquiry*: The five countries do not generally call for students to consistently focus on evidence. This area is an instance of where an exemplar is found in U.S. standards. The recently revised College Board Standards call attention to and consistently incorporate science practices that focus on *establishing lines of evidence, using the evidence to substantiate claims, to develop and refine testable explanations, and to make predictions about natural phenomena*.[2]
- *Chemistry Foundation for Concepts in Modern Biology*: The five countries' Primary and Lower Secondary standards in Biology do not appear to provide a sufficient foundation in chemical bonding, reactions, and some aspects of organic chemistry for students to comprehend essential concepts in modern biology.
- *Interdisciplinary Connections*: With the exception of Earth and Space Science, standards at the Upper Secondary level generally do not highlight fundamental connections between disciplines that would reinforce student understanding of how a concept in one discipline has explanatory power in another.
- *Learning Progressions*: As noted earlier, no individual country's standards were able to serve as an overall exemplar from the Primary through the Upper Secondary levels. A noticeable gap between Lower and Upper Secondary standards in terms of the complexity of content and performance expectations, including the application of mathematics in a number of countries, suggest this is an area that will require close attention as the next-generation U.S. science standards are developed.

Conclusion

Conditions are right for the United States to take the lead internationally in forging a new conceptual framework for science, and next generation science standards. The NRC framework and aligned science standards will create a fresh vision for science education and new directions for teaching, learning, and assessment that could contribute significantly to improving student understanding and achievement. Seizing the opportunity that this moment presents will bring us a step closer to moving the United States into the vanguard of international science education reform.

[1] Philip M. Sadler and Robert H. Tai, "TRANSITIONS: The Two High-School Pillars Supporting College Science," *Science* 27 July 2007 317: [DOI: 10.1126/science.1144214], 457.

[2] The College Board, <u>SCIENCE College Board Standards for College Success</u>, (The College Board, 2009).

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II. INTRODUCTION

NEXT GENERATION SCIENCE STANDARDS

The nation's capacity to innovate for economic growth, and the ability of American workers to thrive in the global economy depend on a broad foundation of math and science learning, as do our hopes for preserving a vibrant democracy and the promise of social mobility for young people that lie at the heart of the American dream.[3]

In that one sentence, the Carnegie Corporation of New York and the Institute for Advanced Study's Commission on Mathematics and Science Education summarized the urgency of the challenge that confronts the nation, its gravity, and the likely consequences of failing to meet it, as well as the opportunity it presents. The Commission's stance is unambiguous: moving forward, the nation's goal must be nothing short of ensuring all high school students graduate STEM-capable (that is, having the option of choosing science, technology, engineering and mathematics careers), ready for college and career. Carnegie subsequently announced its support for the development of a new conceptual framework and aligned science standards to replace the *National Science Education Standards* published in 1996.[4]

The process of developing new science standards will proceed in two stages. In the first stage, the National Research Council (NRC) will create a conceptual framework for the new standards that will identify and articulate the core ideas in science. The NRC framework will consider fundamental ideas in the disciplines of science (life sciences[5], physical sciences, earth sciences, and technology and engineering) along with cross-cutting ideas such as mathematization, causal reasoning, evaluating and using evidence, argumentation, and model development. The framework will be open for review and public comment before it is completed.

In the second stage, Achieve will take the lead and develop the standards document, consistent with the guidelines from the framework that will establish clear statements of what all students in the United States should know and be able to do. The new standards are meant to stimulate the transformation of science education in the United States – to be the starting point for next-generation curriculum, instructional practices and assessments, and teacher development that must follow if there is to be significant improvement in student achievement in science.

The NRC and Achieve[6] will complete this work in partnership with the American Association for the Advancement of Science (AAAS), the National Science Teachers Association (NSTA) and other partners representative of the scientific community, education policy and science education.

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[3] Carnegie Corporation of New York and Institute for Advanced Study, The Opportunity Equation: Transforming Mathematics and Science Education for Citizenship and the Global Economy (Executive Summary, 2009), vii. <http://www.opportunityequation.org/report/executive-summary/>

[4] National Research Council (1996), National Science Education Standards (Washington, DC: National Academy Press)

[5] Throughout this report, the term "Biology" is frequently substituted for "Life Science," which is the common label used in most Primary and Lower Secondary grades. In the countries in this study, as well as in the United States, Biology is the common term for Upper Secondary or high school courses in this discipline.

[6] International benchmarking is an area of growing interest to Achieve. In 2008, Achieve developed, in conjunction with the National Governors Association and the Council of Chief State School Officers, the report *Benchmarking for Success*. And, in 2009, Achieve completed an examination of mathematics and science standards on behalf of the Asia-Pacific Economic Cooperation (APEC) and the U.S. Department of Education for 12 of APEC's 21 member economies. Achieve is currently working on the revision of the 2012 PISA framework for the next assessment in mathematics.

WHY INTERNATIONAL BENCHMARKING

Without question, recent changes in the global economy have had a profound impact on virtually every facet of American life. The United States has little choice but to confront the shifting landscape and determine how to make the new environment work for Americans individually and the nation as a whole. Creating a new set of national science education standards is an important step in that direction. This study is designed to inform that effort by providing an analysis of the science standards in ten countries whose students perform well on international measures and/or countries of interest, for example, those that have drawn attention for their success in improving their educational systems. These are key benchmarks for the United States to draw upon as it works to strengthen the quality and rigor of its science standards and enhance its competitive advantage.[7]

The results of international tests indicate that students in the United States lag behind those in many other countries in developing science knowledge and scientific literacy.[8] Thus, it is crucial to examine the expectations other nations set for their students and how other nations educate their populations. Doing so will allow U.S. educators to learn from others' strengths in the same manner that U.S. corporations have benchmarked most aspects of their businesses for years. The United States has everything to gain by taking stock and establishing next-generation science standards that are internationally benchmarked as the initial step in re-vitalizing our system of science education.

In most countries, an officially sanctioned national standards document sets out the expectations for student learning and performance in science education at the Primary, Lower Secondary, and Upper Secondary school levels. Many other factors influence what students ultimately learn, but standards are designed to promote and constrain possibilities, and they reflect national priorities for science education that help shape students' opportunities to learn and their experiences in the classroom. Standards represent decisions at the national level regarding academic content, performance expectations, and curricular goals – all designed to shape and improve teaching and learning. Standards convey these critical decisions to students and their parents, as well as to the key stakeholders, including school administrators and teachers, teacher educators, curriculum and assessment developers, and the many other education specialists who are entrusted to reach national goals.

There is not one set of science standards in the United States, but 51, a state of affairs that reflects our decentralized approach to public education. With each state and the District of Columbia developing its own educational standards, the result is a patchwork of different science education priorities that vary across the states and have made it difficult for educators and vendors to develop and disseminate coherent instructional materials and assessment tools. Recent research has examined state-by-state differences and brought to light several critical problems that have arisen as a result of this diversity.[9] (Canada also has a de-centralized system, where education is the responsibility of each province. Achieve selected the standards of Ontario to include in this review as a representative and particularly well-executed example of Canada's standards.) Renewed interest in common state standards makes it all the more important to examine the strengths of science education standards of other countries at this critical point in time.

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[7] International benchmarking does not mean that the United States should simply emulate other countries' standards. In recent years, the United States has made significant strides in advancing the research base that underpins science education and also has its own exemplars. It is also the case that there are shortcomings in all of the standards Achieve examined that are equally instructive for improving standards.
[8] National Science Board, Science and Engineering Indicators 2010 (Arlington, VA: National Science Foundation, 2010).
[9] National Research Council, Assessing the Role of K-12 Academic Standards in States (Washington, DC: National Academy Press, 2008), 33.

PURPOSE AND STRUCTURE OF THIS REPORT

Achieve's international benchmarking report *Taking the Lead in Science Education: Forging Next-Generation Science Standards* presents findings from the analysis of science standards in selected countries intended to inform the development of science standards in the United States. This study was motivated by recognition that we live in a global society, and that our citizenry and workforce must keep pace with other nations if we are to continue to thrive in an increasingly interdependent global economy.

This study of science standards in high performing countries and other countries of interest is meant to help answer three questions important to addressing the challenge laid out by the Carnegie Corporation and to informing the development of the next generation science standards for the United States. Achieve's analysis was guided by three key questions:

1. ***SCIENCE THROUGH LOWER PRIMARY SCHOOL:*** *What knowledge and skills do countries expect all students to learn prior to taking discipline-specific high school courses in science?*

   Any effort to define the science knowledge and skills required of all students must address a complex array of issues related to what students will need to be successful in life and on the job and to grapple with personal and social dilemmas that involve science, technology, or engineering. In short, what constitutes a foundation that leads to "scientific literacy" for all students?

   By analyzing the knowledge and skills countries expect all students to learn before taking discipline-specific high school courses in science, we are able to put a finer point on what science-related content and performances countries regard as foundational to scientific literacy. These foundational standards serve two functions: they reflect the expectations countries have for all their students and they establish a base for postsecondary options and could lead to further study in each of the four major fields. (The phrase *foundational scientific literacy* is not meant to imply that students are prepared to meet real-world demands without additional study in discipline specific courses.)

2. ***UPPER SECONDARY SCIENCE:*** *What knowledge and skills do countries expect students to learn in Upper Secondary courses in Biology, Chemistry, Physics, and Earth and Space Science?*

   Like the United States, many of the countries included in our study expect students who will graduate STEM-capable and who intend to pursue postsecondary education at a college, university, or technical institution to take additional discipline-specific courses in science. Thus, the knowledge and skills countries emphasize in these courses is of high interest – the choices countries make reflect the content they think is most important for students to be successful in postsecondary science education. In practice, there are, of course, no hard and fast rules regarding what that content ought to be, and there is no clear distinction between the knowledge and skills that signify that students are scientifically literate and those that signify students are STEM-capable; the expectations for both exist on a continuum. Rather, the distinction reflects choices about the knowledge and skills, when they are introduced and how they are integrated into a progression that extends from the beginning of science instruction through to the transition into postsecondary courses in the scientific disciplines.

3. ***EXEMPLARY FEATURES:*** *What are exemplary features of the standards reviewed in this study that should be considered by developers of next-generation science standards in the United States? What are common shortcomings – and how might they be overcome?*

   All countries are struggling with the pace of change in science, technology, and engineering as well as the need to keep students' education responsive and current. Shortcomings are inevitable. While there is no perfect set of standards, exemplary elements in other countries' standards and in our own efforts can push our thinking as we grapple with constructing new standards. Countries take a variety of approaches in organizing, structuring, and articulating their standards, and also make different choices as to the topics they include and the proficiencies they expect. Each approach not only has different strengths and weaknesses, but also suggests different solutions that may be useful to the next-generation standards-developers.

This report begins with a quantitative analysis, based on the coding of each country's standards documents, that provides a comprehensive look at the coverage of various topics and identifies patterns in the knowledge and skills that countries include in the realms of scientific literacy and STEM-Capability. The second part of the study is a qualitative analysis that examines the different ways that the ten countries included in the study organize, structure and articulate their standards. It next describes exemplary features of five countries' standards, which can be used to inform the NRC framework and the new standards. The report closes with a summary of the conclusions to be drawn from these comparisons and analyses.

SCIENTIFIC LITERACY

Scientific literacy is the primary goal of science education. It is more than mastery of content and skills; it also includes understanding the nature of science, how advances in science are made, and how it affects our lives. Because scientific literacy is essential, two leading perspectives are reviewed below.

Since the mid 1960s, numerous science educators have offered a variety of definitions,[10] as have several prominent organizations.[11]

For the purposes of PISA 2006,[12] *scientific literacy*[13] refers to an individual's:

- Scientific knowledge and use of that knowledge to identify, acquire new knowledge, explain scientific phenomena, and draw evidence-based conclusions about science-related issues
- Understanding of the characteristic features of science as a form of human knowledge and enquiry
- Awareness of how science and technology shape our material, intellectual, and cultural environments
- Willingness to engage in science-related issues, and with the ideas of science, as a reflective citizen.

The four *science practices,* described by the NRC in *Taking Science to School,*[14] offer a holistic view of science as both a body of knowledge and an evidence-based enterprise and describe the following proficiencies (akin to PISA's interpretation) as being essential for scientific literacy:

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[10] Bybee, Rodger W. *Achieving Scientific Literacy: From Purposes to Practices*. Portsmouth, New Hampshire, Heinneman 1997. Pgs. 69-86.

[11] Benchmarks for Scientific literacy, Project 2061 offered the following definition: "[I]n a culture increasingly pervaded by science, mathematics and technology, scientific literacy requires understandings and habits of mind that enable citizens to grasp what these enterprises are up to, to make sense of how the natural and designed worlds work, to think critically and independently, to recognize and weigh alternative explanations of events and design trade-offs, to deal sensibly with problems that involve evidence, numbers, patterns, logical arguments, and uncertainties."

[12] Nine of the ten countries in this study participate in PISA.

[13] OECD, Assessing Scientific, Reading and Mathematical Literacy: A Framework for PISA 2006 (Organisation for Economic Co-Operation and Development, 2006), 12. The Framework goes on to note on p. 20 that three competencies lie at the heart of the definition: identify scientific issues, explain phenomena scientifically and use scientific evidence.

- Strand 1: Know, use, and interpret scientific explanations of the natural world.
- Strand 2: Generate and evaluate scientific evidence and explanations (model building, inquiry, empirical evidence).
- Strand 3: Understand the nature and development of scientific knowledge.
- Strand 4: Participate productively in scientific practices and discourse.

These various aspects of scientific literacy are addressed throughout this report, whether in the discussion of coherence in science standards or the discussion of performance expectations that require students to exercise their reasoning skills or conduct investigations.

Together, these aspects of scientific literacy offer an entry into the ways countries, including the United States, are thinking about science education. By analyzing the connections across the knowledge and skills countries expect all students to learn in science, and how these connections build towards a general understanding of science, we are able to put a finer point on what can be properly understood as the basis for scientific literacy, which provides a foundation for more advanced courses taken later in high school.

COUNTRY SELECTION

Achieve selected countries for inclusion in this analysis based on several criteria. The first was whether a country is a high performer on international assessments: PISA (2006) and TIMSS (2007)[15] and/or important to the United States for economic, political, or cultural reasons. The second was whether the country has standards available in English, and the third was whether the country structures its standards in way that lends itself to the qualitative and quantitative methodology Achieve was to use.

Based on these criteria, Achieve included the standards from the following ten countries in this study:

- Canada [Ontario][16]
- Chinese Taipei
- England
- Finland
- Hong Kong
- Hungary
- Ireland
- Japan
- Singapore
- South Korea

The standing of the selected countries on TIMSS and PISA results, are shown in Table 1.

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[14] Richard A. Duschl, Heidi A. Schweingruber, and Andrew W. Shouse, editors, Taking Science to School: Learning and Teaching Science in Grades K-8 (National Research Council, Committee on Science Learning, Kindergarten Through Eighth Grade. Board on Science Education, Center for Education, Division of Behavioral and Social Sciences and Education, Washington, DC: The National Academies Press, 2007).

[15] See Appendix 1 [separate PDF document].

[16] Achieve analyzed the national standards from each of the included countries, with the exception of Canada, which was represented by standards from the Province of Ontario. Canada delegates responsibility for the development of standards to the provinces, so like U.S. states, each has its own set. Ontario's standards were very clearly written and therefore seemed to be the best choice to represent Canada – throughout the rest of this document references to Canada are referring to the Province of Ontario).

Table 1. TIMSS and PISA Test Scores for Countries Selected for this Analysis[17]

TIMSS 8th Grade (2007)	
Singapore	567
Chinese Taipei	561
Japan	554
South Korea	553
England	542
Hungary	539
Hong Kong	530
United States	520
AVERAGE SCORE	500

PISA (2006) – 15-Year-olds	
Finland	563
Hong Kong	542
Canada	534
Chinese Taipei	532
Japan	531
South Korea	522
England	515
Ireland	508
Hungary	504
OECD AVERAGE SCORE	500
United States	489

For more detailed information on statistically significant differences between the United States and the countries included in this study, including content disciplines, cognition, and science literacy subscales on the most recent PISA and TIMSS international assessments, see Appendix 1.

In addition, Achieve selected sets of exemplary standards from the United States for comparative purposes: Massachusetts' Science and Technology/Engineering Standards (2006); Science: College Board Standards for College Success (2009); and the content statements included in the Science Framework for the 2009 National Assessment of Educational Progress (NAEP) for grades 8, and 12.

[17] National Science Board, Science and Engineering Indicators 2010 (Arlington, VA: National Science Foundation, 2010) 1-21, and 1-23.

III. QUANTITATIVE ANALYSIS

METHODOLOGY

Achieve conducted a quantitative analysis of the standards documents for all ten countries included in this study, modeling the methodology on that developed by Michigan State University for its 1997 study of the content standards and textbooks of countries participating in the Third International Mathematics and Science Study (TIMSS).[18] In that study, researchers developed a coding system that they applied to the designated documents, making it possible to quantitatively compare the content and performances described by the documents of the participating countries.[19] Achieve selected this coding schema because it is uniquely suited for analysis of knowledge and skills across countries and provides an objective tool against which to compare countries' standards.

The TIMSS framework includes over 200 content codes organized into major discipline-based categories – Life Sciences, Physical Sciences, Earth Sciences – and an additional category containing cross-cutting content, such as the *Interaction of Science, Technology and Society*. Achieve modified the categories from the original TIMSS framework to allow chemistry and physics content to be distinguished and to cluster topics in categories familiar to U.S. educators. Achieve also refined a handful of content topics in order to analyze the relationship among categories and the progression of topics across grade spans.

In addition to content codes and descriptions, the TIMSS framework includes codes for performances that generally fall into two general categories: those that are concerned with science content knowledge (cognitive skills) and those concerned with conducting scientific investigations (inquiry skills). Achieve modified the original performance codes to reveal their hierarchical nature. Thus, content experts further characterized the cognitive skills as *Knowing, Applying, or Reasoning*, as is done in the more recently developed TIMSS 2007 Frameworks for Assessment[20]. They also further characterized inquiry skills as either *Basic* or *Advanced*.

Achieve's modified TIMSS Framework:

CONTENT

- Biology
- Chemistry
- Physics
- Earth/Space Science
- Cross-Cutting and Interdisciplinary Content

PERFORMANCE

- Cognitive Demand
  - *Knowing*
  - *Applying*
  - *Reasoning*
- Inquiry Skills
  - *Basic*
  - *Advanced*

The data generated by the coding allowed Achieve to identify quantitative patterns in both *content* and *performance* in the following ways:

- The content topics and performances that individual countries include in their standards;
- The relative attention that individual countries give to these same topics and performances

[18] Schmidt, W.H., McKnight, C.C. & Raizen, S.A., A splintered vision: An investigation of U.S. science and mathematics education (Dordrecht: Kluwer Academic Publishers, 1997). And, Schmidt, W.H., Raizen, S.A, Britton, E.D., Bianchi, L.J. & Wolfe, R.G., Many visions, many aims: A cross-national investigation of curricular intentions, science (Dordrecht: Kluwer Academic Publishers, 1997).
[19] A Splintered Vision provides further detail about this methodology.
[20] Ina V.S. Mullis, Michael O. Martin, Graham J. Ruddock, Christine Y. O'Sullivan, Alka Arora, Ebru Erberber, TIMSS 2007 Assessment Frameworks (International Association for the Evaluation of Educational Achievement, Publisher: TIMSS & PIRLS International Study Center, Lynch School of Education, Boston College, 2005 IEA), 68-72.

within and across the grade spans;
- The emphases individual countries place on knowledge–based vs. inquiry-based performances and their attention to higher-order thinking skills.
- The content categories and performances that most countries include in their standards in each grade span.[21]

The countries Achieve studied organize their education system by grades and/or grade spans through the Primary and Lower Secondary years, then by discipline-based courses in Upper Secondary. The transition from grades with integrated content to discipline-specific courses occurs at the start of the 10th or 11th grade. The students have a common program of study through the end of the Lower Secondary level (ending in the 9th or 10th grade) after which students take courses based on preferences and postsecondary goals.

As shown in Table 2, Achieve examined the standards within three grade spans: Primary (grades 1-6), Lower Secondary (grades 7-9/10), and Upper Secondary (discipline-specific courses taken in grades 10-12). The grade spans and Upper Secondary courses that Achieve coded are listed in Appendix 2.

Table 2: Countries included in Quantitative Analysis

Country	Primary and Lower Secondary	Upper Secondary: Biology, Chemistry & Physics	Upper Secondary: Earth and Space Science
Canada [Ontario]	✓	✓	✓
Chinese Taipei	✓	✓	✓
England	✓	✓	
Finland	✓	✓	
Hong Kong	✓	✓	
Hungary	✓		
Ireland	✓	✓	
Japan	✓	✓	✓
Singapore	✓	✓	
South Korea	✓		

Given that each country requires a common program of study through the end of the Lower Secondary, Achieve characterizes the content and performance expectations that all students should reach by the end of the Lower Secondary as *scientific literacy*. The quantitative analysis allowed the examination of the content expectations through Lower Secondary separate and apart from the additional content and performance expectations included in the Upper Secondary courses. Seeing the general patterns in the content and performances that other countries emphasize in discipline-specific courses helps identify what it means to be prepared for post-secondary work.

[21] For each topic, Achieve calculated the percentage of a country's standards that address the topic based on the total number of codes assigned to the set of standards. Achieve was then able to aggregate the percentage for each topic within each category by country, as well as average the percentage for each topic across all countries.

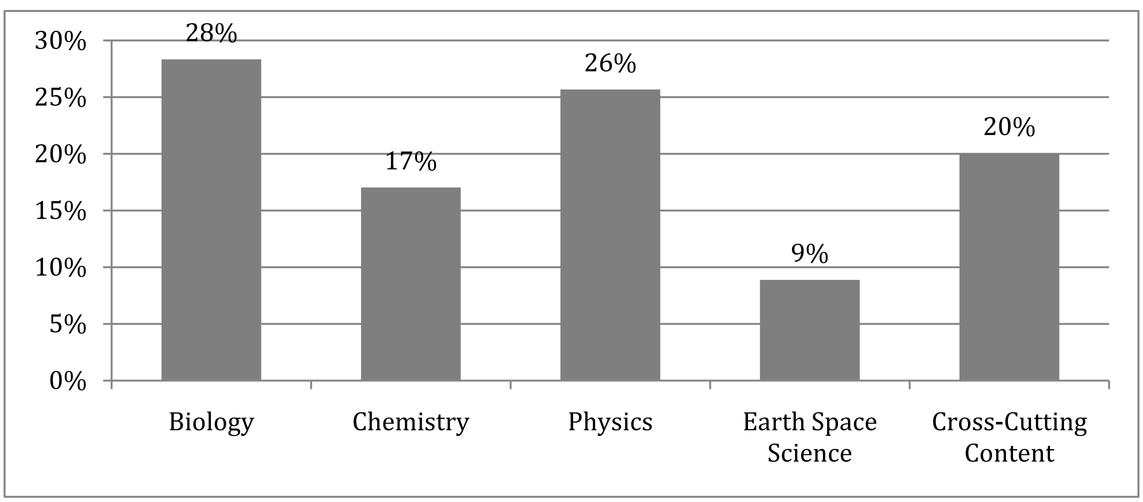
CONTENT EXPECTATIONS[22]

Achieve was able to analyze standards from all ten countries covering the science required for students from Primary through Lower Secondary, and from eight of the ten countries for the additional discipline-specific courses at Upper Secondary that students are also expected to take – but often with flexibility to choose which courses they take (as they do in the United States).[23] The number of countries included in the study is relatively small (n=10), and there are significant variations in the content countries focus on in their standards at the Primary/Lower Secondary and Upper Secondary level. Thus, Achieve found that averages were the most appropriate way of characterizing "big picture" patterns. Nevertheless, in a few instances Achieve found remarkable agreement and takes note of these instances in the findings that follow.

Using the coding data, Achieve first sorted the science standards from the ten countries for Primary and Lower Secondary into the different science disciplines: Biology, Chemistry, Physics, and Earth and Space Science, as well as cross-cutting content. While the countries' standards vary in terms of the proportion of their standards dedicated to each discipline, Achieve calculated the average proportion across the ten countries for each discipline, as shown in Chart 1 below.

On average, the countries dedicate the greatest proportion of their standards to Biology and Physics content. While Biology is the predominant discipline with an average proportion of 28 percent, the Physical Sciences (Physics and Chemistry content) constitute 43 percent of the countries' standards. Earth and Space Science occupies the smallest proportion, with an average of only nine percent. The remaining 20 percent fall under "cross-cutting content."

Chart 1: Average Distribution of Content for Primary through Lower Secondary Grades



Physical Science content predominates at the Primary and Lower Secondary levels – this was an unexpected finding. This category constitutes 50 percent more than the proportion accounted for by

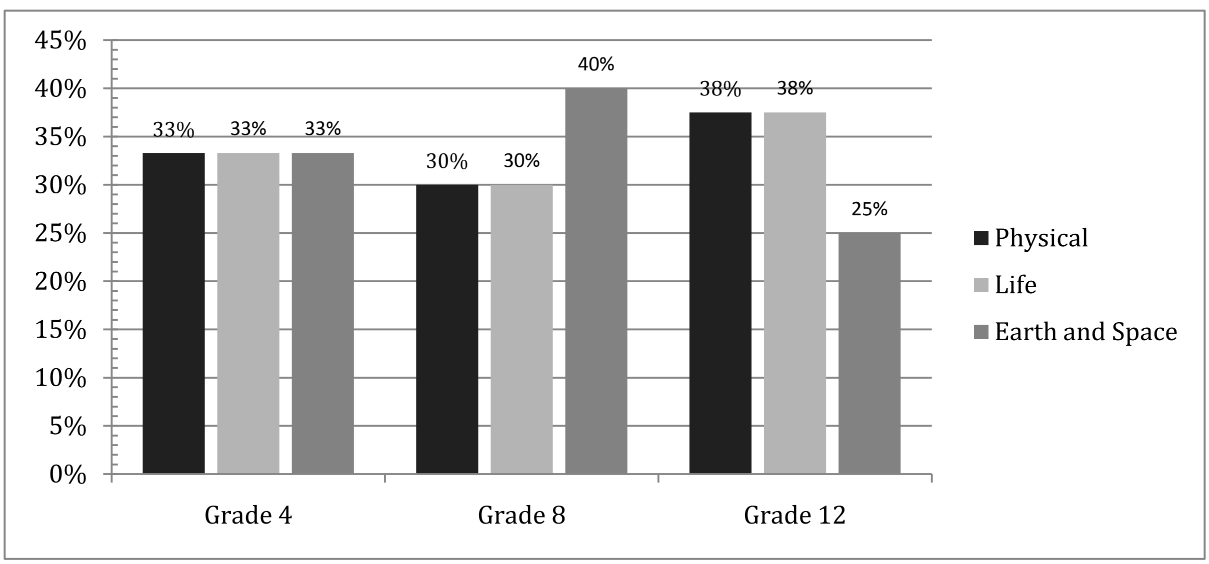
[22]Prior to determining what the ten countries emphasize in terms of content and skills, Achieve identified the science topics that the countries include in their standards statements at each grade span (1-6, 7-9(10), and 10-12). These are listed in Appendix 3 and are shown for the aggregate of countries studied (broken out by discipline and for a set of cross-cutting ideas) for the Primary and Lower Secondary grade spans and for Upper Secondary courses.
[23] With the exception of Earth and Space science that appears to be less common – Achieve analyzed the course standards from three countries.

Biology in the distribution of countries' content standards. The predominance of Physical Science is an instance of remarkable agreement among countries with all placing a premium on this discipline with the exception of Finland, where the emphasis on biology (35 percent) was only slightly greater than on Physical Science (33 percent). This finding is notable for two reasons: first, despite a high degree of variation of content at the topic level, there is a very strong pattern at the discipline level, and second, the pattern is very different from what is typically found in the United States, where Physical Science is not as heavily emphasized in elementary and middle school. A study of a nationally representative sample of state standards from U.S. documents[24] showed that this emphasis on the physical sciences is not shared by most states. It is also not shared by NAEP. As Chart 2 below indicates, NAEP gives equal weight to Life and Physical Science at all three levels (grades 4, 8, and 12); its weight on Earth and Space Science fluctuates with considerable attention at grade 8 and reduced attention at grade 12.

The predominance of Physical Science content in the standards suggests that the participating countries are more concerned than is the United States with providing a strong foundation for Upper Secondary courses in Chemistry and Physics. In addition, this difference in emphasis may help explain the relatively poor performance of U.S. students on TIMSS 2007 in Physics (students in all nine of the countries included in this study that participated scored higher than U.S. students), and in Chemistry (eight of the nine included countries that participated scored higher than the United States). [See Appendix 1.4]

Earth and Space Science topics receive the smallest amount of attention among the science disciplines at the Primary and Lower Secondary levels (less than 10 percent) in the countries in the study, and beyond that light treatment, only three countries include standards for Earth and Space Science at the Upper Secondary level. (A number of countries require Geography, which includes many Earth Science standards in their program of study, and this may account for the discrepancy.) In contrast, the NAEP 2009 Assessment Framework devotes equal weight to each of the major content areas of Life Science, Physical Science, and Earth and Space Science.

Chart 2: NAEP Distribution of Items by Content Area and Grade (% student response time)[25]



[24] Valverde, Gilbert A. and Schmidt, William H., "Greater Expectations: Learning from other Nations in the Quest for "World-Class Standards" in US School Mathematics and Science" (Journal of Curriculum Studies, v32 n5 p651-87 Sep-Oct 2000).
[25] National Assessment of Educational Progress, The Science Framework for the 2009 National Assessment of Educational Progress (National Assessment Governing Board, U.S. Department of Education, U.S. Government Printing Office, 2008), 108.

Cross-Cutting Content

Whether structured using interdisciplinary themes or the scientific disciplines, each country's standards included cross-cutting topics that do not belong naturally or exclusively to a specific discipline. For purposes of this study, cross-cutting content refers to the set of general standards dealing with areas related to all sciences such as: *Nature of Science*, *Interactions of Science, Technology, and Society*, *Sustainability* and the *Nature of Technology/ Engineering* further defined[26] in Figure 1 below.

Figure 1: Cross-Cutting Concepts used in this Study (adapted from TIMSS)[27]

NATURE OF SCIENCE
Nature of Scientific Knowledge • scientific methods, knowledge subject to verification, knowledge subject to change **The Scientific Enterprise** • canons of ethics and decision making, professional communication, the scientific community, personnel and processes in large-scale research efforts • famous scientists, classic experiments, historical development of scientific ideas, industrial revolution (careers), classic inventions
INTERACTIONS OF SCIENCE, TECHNOLOGY AND SOCIETY
Mathematics, technology influence on science • information about contributions of mathematics and technology to development of scientific thought and the practice of science, **Science applications in mathematics, technology** • information about contributions of science to development and practice of mathematics and technology **Influence of science, technology on society** • social, economic, ethical impacts of scientific and technological advances, **Influence of society on science, technology** • information about influence of society on the directions and progress of science and technology
SUSTAINABILITY
Pollution – Causes and Treatment • acid rain, thermal pollution, global warming, water and sewage treatment **Land, Water, Sea Resource Conservation** • rain forest, old growth forests, water supplies **Material & Energy Resource Conservation** • fossil fuels versus alternative energy sources, recycling **World Population** • population statistics, trends; effects of increasing world population **Food Production, Storage** • agricultural methods, food supply and demand, distribution methods **Effects of Natural Disasters** • environmental damages of hurricanes/typhoons, volcanoes, drought
NATURE OF TECHNOLOGY & ENGINEERING
Conceptions of Technology • identifying needs and opportunities, generating a design, planning and making, evaluating **Technologies developed through engineering design** • systems that provide homes and businesses with utilities

[26] Adapted from TIMSS coding framework created for the Third International Mathematics and Science Study (TIMSS) (1995).
[27] See Appendix 3.1 [separate PDF document] for specific Cross-cutting Content category breakdowns.

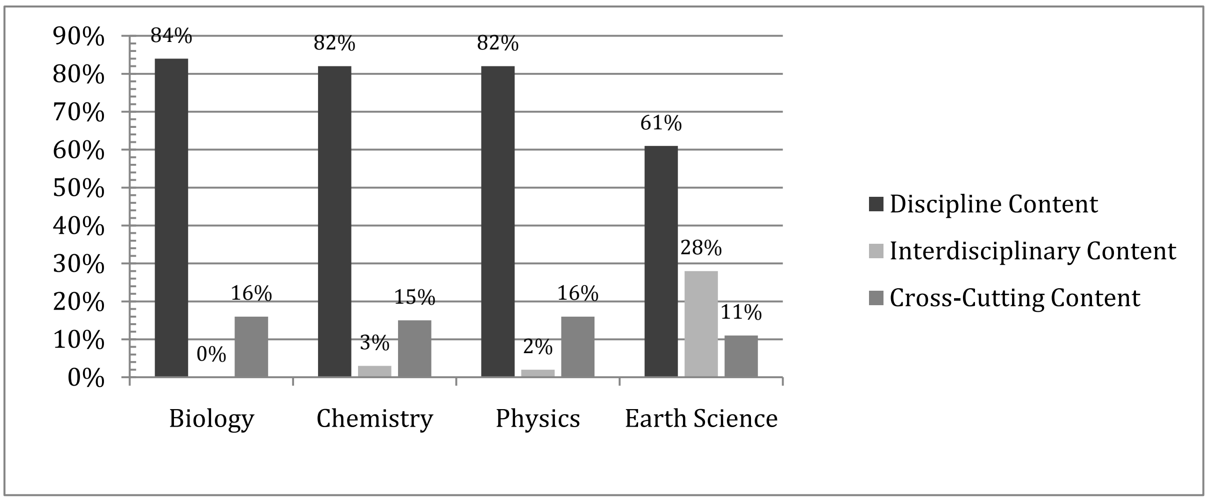
Cross cutting content in Primary and Lower Secondary School

On average, at the Primary and Lower Secondary levels a full 20 percent of content standards are devoted to cross-cutting concepts, such as the *Nature of Science*; *Interactions of Science, Technology, & Society*; and *Sustainability*. This is noteworthy because it indicates the value these countries place on the scientific literacy necessary for understanding and considering science-related issues that affect every citizen, as well as stewardship of our planet.

Cross cutting content in Upper Secondary School

As Chart 3 shows, at the Upper Secondary level, cross-cutting content comprises 16 percent for Biology, 15 percent for Chemistry, 16 percent for Physics, and 11 percent for Earth and Space Sciences. Countries devote appreciable attention to cross-cutting content in their Upper Secondary courses – maintaining the level of emphasis of in the Primary and Lower Secondary grades and, in all areas except biology, adding specific interdisciplinary content.

Chart 3: Average Distribution of Upper Secondary Course Content



Content Distribution by Discipline

As noted earlier, a major challenge that confronts developers of science standards is the overwhelming amount of content that could be included, and the need to distill from it a coherent and manageable set of standards that effectively develops conceptual understanding over time. Thus, it is instructive to see the relative emphases high-performing countries place on familiar content categories in their standards for all students (Primary through Lower Secondary grades 1-10) *within* disciplines; what content is emphasized in Upper Secondary disciplines; and, what shifts in emphasis are revealed as students move from Primary through to Upper Secondary. This information is illustrated in the tables on the following pages.

As explained in the methodology section, each discipline in the modified TIMSS framework is organized on the basis of topics, each of which has a code. Content experts applied these codes, as appropriate, to each standard statement in a country's standards document. The topic codes were then clustered into groups of related topics and then aggregated into *content categories* that represent the main ideas within each discipline. The charts in the following section present data at the *category* level only (Appendix 3 contains *topic*-specific details for all disciplines).

For each discipline, Upper Secondary course standards are first profiled in tables showing the percentage of each *category* of the discipline, along with cross-cutting and interdisciplinary categories represented in the standards statements averaged across all the countries in the analysis. These tables are followed by a more focused presentation showing the percentages of the discipline-specific content *categories* only (i.e., these tables exclude the cross-cutting content and interdisciplinary content categories).

Key content areas important for scientific literacy are identified by examining the tables comparing the emphases of the content *categories* for Chemistry, Physics, Earth and Space Science, and Biology, in the early grade spans (i.e., Primary and Lower Secondary). The analysis then shifts to the Upper Secondary discipline-specific courses, and discusses the content contributing to STEM-capable understandings, and implications for postsecondary preparedness.

CHEMISTRY[28]

Table 3 presents an integrated view of the Upper Secondary Chemistry courses, including not only Chemistry content but also cross-cutting and interdisciplinary content (note that the relative emphasis of Chemistry categories will differ between Table 3 and 4, with the smaller proportions in Table 3 due to the addition of the non-Chemistry content).

Table 3: Upper Secondary Chemistry Course Standards Profile (Chemistry with Cross-Cutting and Interdisciplinary Content Included)

Chemistry Categories	Percent
1. Chemical Reactions	11%
2. Organic Chemistry	10%
3. Chemical Bonding and Molecular Structure	9%
4. Chemical Periodicity	7%
5. Nature of Science*	7%
6. Atomic Structure	5%
7. Stoichiometry	5%
8. Energy and Physical/Chemical Change	3%
9. Interactions of Science, Technology and Society*	3%
10. Kinetics and Equilibrium	3%
11. Properties of Matter	3%
12. Sustainability*	3%
13. Biology-Related Chemistry**	2%
14. Classification of Matter	2%
15. Solids, Liquids, Gases (Kinetic-Molecular Theory)	2%
16. Solutions	2%
17. Earth/Space Science-Related Chemistry**	1%
18. Quantum Theory	1%
19. Physics-Related Chemistry**	<1%
20. Nature of Technology/Engineering*	<1%

*Cross-cutting Content Categories
**Interdisciplinary Content Categories

In order to compare Chemistry categories across grade spans, it is necessary to exclude the cross-cutting content categories and interdisciplinary content (indicated by shading in the table above) from the universe of codes that are embedded in Upper Secondary Chemistry course standards. On average, across the countries in this study, the Chemistry-specific content constitutes 82 percent of the Chemistry Course standards at the Upper Secondary Level (data from eight countries).

Table 4 presents the average proportion of countries' standards devoted to each of the categories of Chemistry for Primary, Lower Secondary, and Upper Secondary courses.

[28] Detailed tables for all disciplines at all grade spans are provided in Appendix 3 [separate PDF document]; these also give data concerning the topics included under each content category.

Table 4: Comparing Chemistry Categories across Grade Spans[29] (Chemistry Content Only)

CHEMISTRY CONTENT Categories	Primary	Lower Secondary	Upper Secondary
1. Organic Chemistry	0%	3%	15%
2. Properties of Matter	24%	16%	13%
3. Chemical Reactions	10%	13%	13%
4. Chemical Bonding and Molecular Structure	1%	7%	11%
5. Stoichiometry	0%	2%	9%
6. Chemical Periodicity	0%	6%	9%
7. Atomic Structure*	<1%	11%	6%
8. Kinetics and Equilibrium	<1%	2%	6%
9. Energy and Physical/Chemical Change*	26%	18%	5%
10. Solids, Liquids, Gases (Kinetic-Molecular Theory)*	19%	7%	5%
11. Solutions	7%	4%	3%
12. Classification of Matter	11%	9%	3%
13. Quantum Theory*	0%	2%	1%

*Physics and Chemistry coding schemes include four clusters that overlap, i.e., they contain content that is often included in high school standards in both disciplines. These are *Atomic Structure, Energy & Physical and Chemical Changes, Quantum Theory,* and *Solids, Liquids, Gases (Kinetic-Molecular Theory).*

Role of Chemistry in Primary through Lower Secondary

Primary Chemistry standards fall into six key categories (those exceeding 1 percent), while Lower Secondary standards expand to 13 categories. Additions include – *Organic Chemistry*, *Chemical Bonding and Molecular Structure, Chemical Periodicity*, *Atomic Structure*, *Stoichiometry, Kinetics and Equilibrium* and *Quantum Theory* – concepts not expected to be taught at Primary. These 13 categories are major chemistry-related conceptual areas of scientific literacy, as described by the ten countries in our sample. *Properties of Matter* and *Energy and Physical/Chemical Change* receive the most attention at the Primary level, followed by *Solids, Liquids, and Gases*. All three categories are maintained at the lower (and Upper Secondary levels) but receive progressively less emphasis across the grades. Thus, Achieve concludes that the foundation for the fundamental concepts encompassed by the three categories is laid in Primary and Lower Secondary, permitting instruction to focus on the more complex aspects of the concepts in the Upper Secondary grades and to also introduce more advanced topics, such as *Stoichiometry.* (See note on postsecondary preparation below.)

Atomic Structure is an important category in both Chemistry and Physics (see Table 6), which indicates that the related topics (elementary atomic theory, subatomic particles, isotopes, and nuclear reactions) are considered by countries to be important areas of conceptual understanding in both disciplines. It also represents an area of opportunity for the developers of the next-generation U.S. science standards to consolidate the treatment of concepts to avoid duplication of instruction in two high school courses and encourage in-depth treatment and recognition of the connections among the science disciplines.

[29] Data in this and similar tables represent averages across all countries in the study. These data can be distorted by an outlier. For example, in deriving the average for a category at the Upper Secondary level, such as *Systems, Organs, Tissues: Structure and Function*, one country registers 28 percent, well beyond the next highest at 14 percent.

Upper Secondary Chemistry Course Profiles – Preparation for Postsecondary Education

What countries expect of students in Upper Secondary Chemistry courses that extend beyond scientific literacy has implications for next-generation high school standards. The following categories represent the most emphasized content at the Upper Secondary level: *Organic Chemistry; Properties of Matter; Chemical Reactions; Chemical Bonding and Molecular Structure; Stoichiometry; Chemical Periodicity;* and *Atomic Structure.*

One surprise finding is the predominance of organic chemistry at the Upper Secondary level. The standards of three countries (Hong Kong, Singapore, and Ireland) place significantly more emphasis on organic chemistry than do the standards of the remaining five countries included in the study at Upper Secondary. These three countries give the most attention to hydrocarbons, types of organic reactions, and functional groups and properties, while giving comparatively little attention to topic of biochemical changes. The latter finding reinforces the finding from the analysis of Biology (discussed below) regarding the lack of a cohesive approach to the chemical underpinnings of modern biology and the resulting need to connect the two disciplines so students understand more and memorize less.

Achieve deliberately broke out stoichiometry as a separate category in the coding of Chemistry, rather than considering it as a sub-topic under chemical reactions, because we were interested in tracking the degree to which countries called for students to apply mathematics to chemical reactions. (Thus, a standard that called for students to write word equations was not coded under this category, but one that called for students to solve problems converting among moles, mass, volume and numbers of particles was). The data reveal that the mathematics of chemistry receives a significant amount of attention in countries' Upper Secondary courses. What is important to note is that the mathematics required for introductory stoichiometry only involves basic arithmetic and simple direct and indirect equations, but these simple applications greatly enhance students' understanding of the predictive power of a chemical equation.

PHYSICS

Table 5 presents a profile of the Upper Secondary Physics course expectations, which includes not only traditional discipline content but also shows the comparative weight of interdisciplinary and cross-cutting content (note that the relative emphasis of Physics categories will differ between Table 5 and Table 6, with the smaller proportions in Table 5 because of the addition of the non-Physics content).

The countries' Upper Secondary Physics course standards include a significant focus on *Interactions: Science, Technology & Society*. It is interesting to note that the *Nature of Technology and Engineering* category is not represented among the Upper Secondary Physics standards.

Table 5: Upper Secondary Physics Course Standards Profile (Physics with Cross-Cutting and Interdisciplinary Content Included)

Physics Categories	Percent
1. Motion and Newton's Laws	16%
2. Electrical Phenomena	10%
3. Interactions of Science, Technology and Society*	10%
4. Energy and Physical/Chemical Change	8%
5. Forces	7%
6. Wave Phenomena	7%
7. Atomic Structure	6%
8. Electromagnetism	5%
9. Light and Optics	5%
10. Quantum Theory	5%
11. Work, Energy, Power	5%
12. Nature Of Science*	4%
13. Magnetic Phenomena	3%
14. Solids, Liquids, Gases (Kinetic-Molecular Theory)	3%
15. Chemistry-Related Physics**	1%
16. Earth/Space Science-Related Physics**	1%
17. Fluid Mechanics	1%
18. Relativity	1%
19. Sustainability*	1%
20. Biology-Related Physics**	<1%
21. Nature of Technology and Engineering*	<1%

*Cross-cutting Content Categories
**Interdisciplinary Content Categories

In order to compare Physics categories across grade spans, it is necessary to exclude the cross-cutting content categories and interdisciplinary content (indicated by shading in the table above) from the universe of codes that are embedded in Upper Secondary Physics course standards. On average, across the countries in this study, the Physics-specific content constitutes 82 percent of the Physics course standards at the Upper Secondary Level (data from eight countries).

Table 6 presents Achieve's findings comparing the average proportion of countries' standards devoted to each of the categories of Physics for Primary, Lower Secondary, and Upper Secondary courses.

Table 6: Comparing Physics Categories across Grade Spans (Physics Content Only)

PHYSICS CONTENT Categories	Primary	Lower Secondary	Upper Secondary
1. Motion and Newton's Laws	14%	9%	19%
2. Electrical Phenomena	11%	13%	12%
3. [30]Energy and Physical/Chemical Change*	15%	14%	10%
4. Atomic Structure*	<1%	9%	8%
5. Forces	7%	6%	8%
6. Wave Phenomena	7%	6%	8%
7. Work, Energy, Power	14%	12%	7%
8. Light and Optics	9%	12%	6%
9. Quantum Theory*	0%	2%	6%
10. Electromagnetism	7%	7%	6%
11. Magnetic Phenomena	5%	2%	3%
12. Solids, Liquids, Gases (Kinetic-Molecular Theory)*	11%	5%	3%
13. Fluid Mechanics	1%	3%	2%
14. Relativity	0%	<1%	<1%

*Physics and Chemistry coding schemes include four clusters that overlap, i.e., they contain content that is often included in high school standards in both disciplines. These are *Atomic Structure, Energy & Physical and Chemical Changes, Quantum Theory,* and *Solids, Liquids, Gases (Kinetic-Molecular Theory).*

Role of Physics in Primary through Lower Secondary

The 13 categories (excluding relativity) included in Table 6 under Lower Secondary are the major conceptual areas of scientific literacy as described by the ten countries in our sample. Primary Physics standards fall into 11 key categories (a category is included if it equals or exceeds 1 percent of the Physics standards), while Lower Secondary standards expand to 13 Physics categories with the addition of *Atomic Structure*, *Quantum Theory,* and *Relativity*. *Energy and Physical/Chemical Change*, *Motion and Newton's Laws*, and *Work, Energy, Power* emerge as the three dominant categories in Primary, followed closely by *Electrical Phenomena,* and *Solids, Liquids, Gases*. In general, countries continue to attend to these categories in Lower Secondary, although the category of *Motion and Newton's Laws* receives

[30] Note: Four categories are common to both Chemistry and Physics (*Energy and Physical/Chemical Change* and *Solids; Liquids and Gases (Kinetic Molecular Theory); Atomic Structure*; and, *Quantum Theory*). In the methodology of the study, they are counted in both disciplines. However, when comparing the percentages listed for these categories at Primary and Lower Secondary (see Tables 6 and 8) there are apparent differences. In Primary and Lower Secondary, the countries' Chemistry and Physics standards are integrated, i.e., they are grouped together as "physical science" – not separated by content areas as they are in Upper Secondary. In the organization of the study data, all the standards relating to these categories are applied to both Chemistry and Physics groupings. The percentage shown, for example in *Energy and Physical/Chemical Change,* in Primary level Chemistry is 26 percent, while the same category in Physics at the Primary level is 15 percent. This difference arises since the number of *Energy and Physical/Chemical Change* coded standards is fixed, while the total number of Chemistry standards is different from the total number of Physics standards, i.e., the denominators are different. This accounts for the same apparent differences in percentage shown for each of the common categories in Primary and Lower Secondary.

decreasing emphasis until Upper Secondary, where it receives significantly more attention than any other category.

Role in Upper Secondary School

In Physics, we find that the emphases of content generally follow the structure of the earlier grades' standards, although *Quantum Theory* receives increased attention.

The following Physics categories represent the most emphasized content in Upper Secondary and are reasonably supported by related standards in the lower grades: *Motion and Newton's Laws; Electrical Phenomena; Energy and Physical/Chemical Changes; Forces; Wave Phenomena; Atomic Structure;* and *Work, Energy, Power.*

Motion and Newton's Laws are emphasized across the Primary, Lower Secondary, and Upper Secondary levels, though of course the actual content differs, shifting from describing motion, to observing patterns and then to taking up Newton's laws quantitatively at the Upper Secondary level.

EARTH AND SPACE SCIENCE

Table 7 presents an integrated view of the Upper Secondary Earth and Space Science courses, including not only Earth and Space Science content but also cross-cutting and interdisciplinary content (note that the relative emphasis of Earth and Space Science categories will differ between Tables 7 and 8, with the smaller proportions in Table 7 due to the addition of the non-Earth and Space Science content).

Table 7: Upper Secondary Earth and Space Science Course Standards Profile (Earth and Space Science with Cross-Cutting and Interdisciplinary Content Included)

Earth and Space Science Categories	Percent
1. Earth's Features and Materials	20%
2. Physics-Related Earth/Space Science**	19%
3. Weather and Climate	12%
4. The Universe	9%
5. Solid Earth Processes	8%
6. The Solar System	7%
7. Biology-Related Earth/Space Science**	6%
8. Sustainability	5%
9. Geological Time	4%
10. Chemistry-Related Earth/Space Science**	3%
11. Interactions of Science, Technology and Society*	3%
12. Nature of Science*	3%
13. Biogeochemical Cycles	1%
14. Nature of Science*	<1%
15. Nature of Technology and Engineering*	<1%

*Cross-cutting Content Categories
**Interdisciplinary Content Categories

In order to compare Earth and Space Science categories across grade spans, it is necessary to exclude the cross-cutting content categories and interdisciplinary content (demarcated by shading in the table above) from the universe of codes that are embedded in Upper Secondary Earth and Space Science course standards. On average, across the countries in this study, the Earth and Space Science-specific content constitutes 64 percent of the Earth and Space Science course standards at the Upper Secondary level for the three countries with Earth and Space Science courses.

Achieve did not find a significant number of interdisciplinary content standards in Biology, Chemistry, or Physics. We did, however, find that more than a quarter of the Earth and Space Science course standards are related to the disciplines of Biology, Chemistry, and Physics. Physics-related content is predominant among the interdisciplinary content in Earth and Space Science.

The relatively high percent of interdisciplinary connections in Earth and Space science relative to the other major fields is not unexpected since it is an area to which other sciences are applied in an integrated fashion. For example, the theory of plate tectonics rests on fundamental laws of heat transfer within Earth's geosphere, while theories of climate change rely on understanding of heat transfer within the atmosphere, as well as the chemistry of the atmosphere and oceans, the role played by living organisms in ecosystems, and so on. To the extent that a new generation of science standards is to focus on science literacy, Earth and Space Science offers unique opportunities to illustrate the importance of cross-disciplinary investigations in the context of real-world issues.

Table 8 presents Achieve's findings comparing the average proportion of countries' standards devoted to each of the categories of Earth and Space Science for Primary, Lower Secondary, and Upper Secondary courses.

Table 8: Comparing Earth and Space Science Categories across Grade Spans (Earth and Space Science Content Only)

EARTH AND SPACE SCIENCE Categories	Primary	Lower Secondary	Upper Secondary
1. Earth's Features and Materials	17%	24%	33%
2. Weather & Climate	27%	27%	19%
3. The Universe	6%	10%	14%
4. Solid Earth Processes	6%	9%	13%
5. The Solar System	34%	12%	13%
6. Geological Time	1%	10%	7%
7. Biogeochemical Cycles	9%	7%	2%

The table above represents the Earth and Space Science data from all ten countries combined at the Primary and Lower Secondary levels, and from just three countries at the Upper Secondary level. (Chinese Taipei, Japan, and Canada are the only countries that have Upper Secondary courses in this discipline.) The table breaks out by percentages for each level, rank-ordered by emphasis at the Upper Secondary level.

Role of Earth and Space Science in Primary through Lower Secondary

Primary Earth and Space Science standards fall into seven categories. These same categories also appear at the Lower Secondary level, indicating that these are the major conceptual areas of scientific literacy as defined by the ten countries in our sample.

The following categories represent the most emphasized content at the Upper Secondary level and are reflected in the related standards in the lower grades: *Earth's Features and Materials; Weather and Climate; The Universe; Solid Earth Processes and The Solar System.*

Role of Earth and Space Science in Upper Secondary School

In Earth and Space Science, two of the top three categories remain the same across all grade spans: *Weather & Climate* and *Earth's Features and Materials*. It is also important to note that the three countries that have Earth and Space Science standards at the Upper Secondary level include many standards that relate to Physics content (See Table 7).

Just three countries in this study (Chinese Taipei, Japan, and Canada) include Earth and Space Science as an Upper Secondary course offering. As was the case for the other disciplines, the content emphases generally follow the structure of the earlier grades' standards but Upper Secondary gives more attention to the category, *Earth's Features and Materials* and *Solid Earth Processes* and less attention to *Weather and Climate*.

It appears that Earth and Space Science is not a priority at the Upper Secondary level for the countries in the study. Some countries have courses in Geography that include a number of concepts found in traditional Earth and Space Science courses. However, it seems that most of these countries intend their students to master the bulk of the Earth and Space science content by the end of the Lower Secondary level.

BIOLOGY

Table 9 presents a holistic view of the Upper Secondary Biology courses, including not only Biology content, but also cross-cutting and interdisciplinary content (note that the relative emphasis of Biology categories will differ between Table 9 and Table 10; the smaller proportions in each Biology category in Table 9 is the result of the addition of the non-Biology specific content, e.g., *Nature of Science*, etc., displayed in the shaded rows).

Table 9: Upper Secondary Biology Course Standards Profile (Biology with Cross-Cutting and Interdisciplinary Content Included)

Biology Categories	Percent
1. Cells: Structure and Function	14%
2. Systems, Organs, and Tissues: Structure and Function	12%
3. Human Biology: Health and Physiology	10%
4. Reproduction, Development and Heredity	10%
5. Nature of Science*	9%
6. Homeostasis	9%
7. Modern Genetics	9%
8. Interaction and Interdependence in Living Things	7%
9. Biodiversity	5%
10. Interactions of Science, Technology and Society*	5%
11. Sustainability*	4%
12. Evolution	4%
13. Earth/Space Science-related Biology**	<1%
14. Nature of Technology/Engineering*	<1%
15. Chem/Physics-related Biology**	<1%

*Cross-cutting Content Categories
**Interdisciplinary Content Categories

In order to compare Biology categories across grade spans, it is necessary to exclude the cross-cutting content categories and interdisciplinary content (demarcated by shading in the table above) from the universe of codes that are embedded in Upper Secondary Biology course standards. The Biology-specific content constitutes 84 percent of the Biology Course standards at the Upper Secondary level (eight countries) in this study include standards in Upper Secondary Biology courses and are represented in this data).

Table 10 presents the average proportion of countries' standards devoted to each of the categories of Biology for Primary, Lower Secondary, and Upper Secondary courses.

Table 10: Comparing Biology Categories across Grade Spans (Biology Content Only)

BIOLOGY CONTENT Categories	Primary	Lower Secondary	Upper Secondary
1. Cells: Structure & Function	2%	10%	18%
2. Reproduction, Development & Heredity	15%	11%	15%
3. Systems, Organs, and Tissues: Structure & Function	12%	18%	13%
4. Homeostasis	13%	11%	11%
5. Modern Genetics	0%	3%	11%
6. Biodiversity	17%	10%	9%
7. Human Biology: Health & Physiology	21%	18%	9%
8. Interaction and Interdependence in Living Things	19%	16%	8%
9. Evolution	2%	3%	5%

Role of Biology Primary through Lower Secondary

Primary Biology standards fall into eight categories, while Lower Secondary standards expand to nine Biology categories with the addition of *Modern Genetics*, as shown in Table 10. These categories are the major Biology conceptual areas of scientific literacy as defined by all ten countries in our sample. At the Primary level, countries on average direct the greatest amount of attention to four categories: *Human Biology: Health & Physiology (21%)*; *Interaction and Interdependence in Living Things (19%); Biodiversity (17%); and Reproduction, Development and Heredity (15%)*.

At the Lower Secondary level these categories generally receive the same level of emphasis, with the exception of *Systems, Organs, and Tissues: Structure and Function*, which becomes one of three categories emphasized at Lower Secondary (the others being *Human Biology: Health and Physiology* and *Interaction and Interdependence in Living Things*.) The remaining science categories on average receive no more than 5 percent of emphasis.

An emerging general pattern for Primary through Lower Secondary is that countries' standards in the biological sciences have a relatively strong focus on human biology and relationships among living things – topics of importance in scientific literacy from a personal perspective, and environmental issues. As discussed below, many states in the U.S. require courses in health in this grade span in addition to their science programs. (This study did not examine international standards related to programs targeted specifically at human health and physiology.) Attention to the societal perspective is seen in the relative emphases placed on two related cross-cutting categories – *Sustainability,* and *Interactions of Science, Technology and Societ*y.

Role of Biology in Upper Secondary School

The following categories represent the most important content at the Upper Secondary level: *Cells: Structure & Function; Reproduction, Development & Heredity; Systems, Organs, and Tissues: Structure & Function; Homeostasis; and Modern Genetics*. All of the categories, except *Modern Genetics*, tend to be introduced at the Primary level, maintained or further developed in Lower Secondary, and elaborated in Upper Secondary courses.

BIOLOGY – A Closer Look: Comparing International and Exemplary U.S. Biology Standards

If Physical Science is broken out into Chemistry and Physics content, then Biology receives the most emphasis of all the science disciplines internationally. Biology is also the most common course taken by U.S. high school students.[31] Given biology's leading position in science education and its growing reliance and connections to the physical sciences, especially chemistry, this study examined the differences between selected U.S. exemplars and the international countries in terms of the relative emphasis they place on biology content categories, including those that have to do with the chemistry of living things.

Achieve selected and coded three sets of exemplary U.S. documents for comparison with the international standards. The U.S. biology standards come from *Massachusetts' Science and Technology/Engineering Standards (2006)* and, *Science: College Board Standards for College Success (2009).* The third document (the *NAEP 2009 Science Assessment Framework* life science content statements for grades 8 and 12) is not a set of course-based standards, but provides a national perspective on science education and achievement valued by policy makers and the science community. These documents are not representative of state standards in general, but rather represent the leading edge in U.S. content and performance expectations in the life science.

Biology has undergone a major transformation from a focus on description and categorization of life forms to a focus on conceptual understanding and core principles. The College Board takes note of the shift in its introduction to the life science standards. *"The standards represent the shift in the College Board's view of rigor, from requiring that students know all of the facts, vocabulary, and specific examples related to various topics, to ensuring students' understanding and application of core principles for the discipline and the integration of this knowledge with the skills essential for practicing science.*[32]

One concern is that both U.S. and international biology standards have not generally kept pace with advances in preparing students for understanding the molecular structure of cells and cell organelles, homeostasis, and genetics, including the central role of proteins in life functions. For example, in ACT's[33] Model Course Syllabus – Science – Biology, an area of major emphasis is *Taxonomy*. This includes topics such as *Classification of living things, Use of dichotomous keys, Major phyla, Organisms, Bacteria and viruses, Animals, Invertebrates, and Vertebrates*. While an appreciation for the diversity of life and grasping the rudiments of classification are important, the time spent mastering Taxonomy content at the level implied by the above list of topics could come at the expense of comprehending fundamental ideas in biological chemistry.

The average biology category rankings for this data are shown in Table 11 alongside the international averages.

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[31] According to the National Center for Education Statistics, 92 percent of public and private high school graduates in 2005 completed a biology course. For more information, see Table 149 in the Digest of Education Statistics 2008 (National Center for Education Statistics, Institute of Education Sciences, U.S. Department of Education. Washington, DC.).
[32] The College Board, SCIENCE College Board Standards for College Success (The College Board, 2009), 50.
[33] ACT, On Course for Success – A Close Look at Selected Courses That Prepare All Students for College (ACT, Inc., 2006), 62.

Table 11: Biology Averages – Comparison between U.S. Exemplary Standards and International Countries' Standards for Lower Secondary*

Biology Categories**	U.S. Exemplars Averages Grades 6-8	International Average Lower Secondary
1. Human Biology: Health & Physiology	0%	18%
2. Systems, Organs, and Tissues: Structure and Functions	7%	18%
3. Interaction and Interdependence in Living Things	20%	16%
4. Homeostasis	10%	11%
5. Reproduction, Development & Heredity	10%	11%
6. Biodiversity	14%	10%
7. Cells: Structure & Function	19%	10%
8. Evolution	14%	3%
9. Modern Genetics	6%	3%

*Table 11 is not an exact comparison since the U.S. standards represent grades 6-8 and grades 5-8 in the case of NAEP, while the data for the international set generally span grades 7 through 10, and in three countries, grades 7 through 9. The comparison attempts to show differences in content emphasis in the grade spans just prior to students taking discipline-based science courses.

**Table rank-ordered based on International standards' averages

On average, United States' exemplar life science standards do not share the emphasis on *Human Biology: Health & Physiology* that the international standards do. This category is virtually absent among the U.S. exemplars. To illustrate, while Massachusetts' students in grades 6-8 are exposed in a general way to the physiology of the human body, they learn about human systems in the context of related vertebrate organisms. The lack of attention to human biology may stem from the fact that most states have a high school health requirement which covers this content: 21 states require a semester of health; 4 require a year of health; 12 blend health and physical education together; only 14 states do not require a health course.[34] That said, many of the health courses are not taught by teachers certified in Biology so the content is likely not well coordinated with, or representative of the rigor of states' high school Biology standards.

In contrast, the categories of *Systems, Organs, and Tissues: Structure and Functions; Homeostasis, Reproduction, Development & Heredity;* and *Cells: Structure & Function* represent more than 50 percent of the international standards at the Lower Secondary level, matched closely by the U.S. at 46 percent.

U.S. exemplars place somewhat more emphasis on *Interaction and Interdependence in Living Things* (20 percent) than do the international countries (16 percent). *Evolution* ranks among the top four categories in the U.S. exemplars (14 percent), while the international standards place this category at the bottom of their rankings (3 percent). The category *Biodiversity* represents 10 percent of the international Biology standards. This is surpassed by the U.S. exemplar standards with an average of more than 14 percent. *Modern Genetics* is treated lightly among the international standards at 3 percent, while it receives twice that emphasis on average by the U.S. exemplars (6 percent).

Similar comparisons were made between the international Upper Secondary courses and the U.S. exemplary high school standards. Table 12 presents these data.

[34] Achieve, Inc., Fall 2009 – unpublished data from Achieve's annual survey of all 50 states and the District of Columbia.

Table 12: Biology Averages – Comparison between U.S. Exemplary Standards and International Countries' Standards for Upper Secondary

Biology Categories*	U.S. Exemplar Average High School	International Average Upper Secondary
1. Cells: Structure & Function	16%	18%
2. Reproduction, Development & Heredity	15%	15%
3. Systems, Organs, and Tissues: Structure and Functions	6%	13%
4. Homeostasis	12%	11%
5. Modern Genetics	20%	11%
6. Biodiversity	9%	9%
7. Human Biology: Health & Physiology	1%	9%
8. Interaction and Interdependence in Living Things	12%	8%
9. Evolution	8%	5%

*Table rank-ordered based on International standards averages

The countries in this study and the U.S. exemplars all rank *Cells: Structure & Function*, and *Reproduction, Development & Heredity* at the top of the list of Biology categories. Other countries include *Systems, Organs, and Tissues: Structure and Functions*, whereas U.S. standards include *Modern Genetics* in the top rank. *Modern Genetics*, at 20 percent for the U.S. exemplars, receives almost twice the emphasis that the international set places on that category. It is worth noting that *Modern Genetics*, along with *Cells: Structure & Function*, and *Reproduction, Development & Heredity* are strongly based in bio-chemical concepts at the molecular level.

One recent study provides a U.S. postsecondary perspective on topics taught in entry level-college courses.[35] The authors observe: *Of all the Biology topics, Molecules and Cells was the most strongly emphasized in course syllabi.* They also found that *Molecules, Cellular Energetics*, and *Molecular Genetics* include more than one quarter of all the biology topics covered in the entry-level higher education Biology courses they studied. These topics are all concerned with the chemistry of life. If students are to be prepared for the demands of postsecondary courses in life science, they clearly need to have a solid grasp of related chemistry concepts.

A review of the patterns of emphasis in these categories in other countries' standards across the grade spans (see Appendix 3 for more detail) reveals a lack of attention to critical biochemistry concepts that are necessary for students to understand the bio-molecular content in Upper Secondary Biology – a weakness that has surfaced in Achieve's reviews of U.S. standards as well. A partial break-out of the topics found in these categories from the coding scheme used in this study illustrates the need for a foundation in basic chemistry:

- Biochemistry of genetics (concept of the gene)
- DNA, the hereditary substance
- Structure of DNA
- Replication mechanism DNA → DNA;
- Transformation of DNA replication mechanism DNA → RNA

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[35] David T. Conley, and Carla J. Bowers, *Analyzing College Science Course Content: Implications for Instruction and System Alignment*, (University of Oregon, Presented at the annual meeting of the American Educational Research Association, March, 2008, New York, NY).

- Biochemical processes in cells
- Chemical composition of biological organisms
- Chemistry of cells (enzymes)
- Cell communication and regulation
- Cell water relations

The U.S. exemplars point the way to more emphasis on modern biology. For example, College Boards' Objective LS.2.2 – Cell Structure *(Students understand that cells have internal structures that carry out specialized life functions and that these internal structures vary depending on a cell's function)* includes Suggested Connections to chemistry concepts such as *Structure–Property Relationships* (C.2.2 – Students understand the relationship between molecular-level structure and chemical and physical properties); *Chemical Equilibrium* (C.2.4 – Students understand that many reactions do not proceed completely from reactants to products; instead, reactions reach a state of dynamic equilibrium where the amounts of reactants and products appear constant.); and *Chemical Kinetics* (C.2.5 – Students understand that for a chemical reaction to occur, reacting particles must collide in the appropriate orientation with enough energy to overcome the activation energy barrier).

In a related ESSENTIAL KNOWLEDGE statement (*Enzymes are proteins that enable chemical reactions to proceed at rates that support life functions. Environmental factors and modulators (inhibitors and activators) influence an enzyme's activity and its ability to regulate chemical reactions (i.e., life's essential functions),* College Board is careful to establish an instructional content limitation by including a *BOUNDARY: The targets of understanding are (1) changes in reaction rates due to enzymes, and (2) the factors that affect enzymes. Quantitative treatment of reaction rates is out of the scope of this objective. The molecular orientation of molecules (i.e., tertiary structure) and the specific enzyme mechanism (i.e., induced fit) are also not appropriate.*[36]

Based upon the study by Conley and Bowers, who also noted that 54 percent of topics concerned with *"Molecules and Cells"* (for example: chemical composition of organisms; chemical bonding patterns; unique properties of water; cellular energetics, e.g., free energy, ATP hydrolysis, coupled reactions, generalized metabolism; enzyme structure and function; cellular respiration, i.e., aerobic, anaerobic; photosynthesis, i.e., conversion of radiant energy to chemical bond energy) is taught as "new material" in college entry-level biology courses[37], it appears that U.S. state-level life science standards do not give sufficient attention to essential chemistry concepts, either in middle school or within high school biology course work. These chemistry understandings underpin and support student understanding of important elements of the chemistry of living systems.

[36] The College Board, SCIENCE College Board Standards for College Success (The College Board, 2009), 59 and 61.
[37] David T. Conley, and Carla J. Bowers, *Analyzing College Science Course Content: Implications for Instruction and System Alignment*, (University of Oregon, Presented at the annual meeting of the American Educational Research Association, March, 2008, New York, NY), 45, 72.

PERFORMANCE EXPECTATIONS

Achieve also analyzed the performance expectations articulated in standards documents. These expectations are foundational in two senses of the word; they represent the proficiencies that countries consider essential for all citizens, and they also lay the bedrock preparation for those students who will be pursuing further, more demanding coursework in the sciences at the Upper Secondary level.

Achieve's goal was to determine the relative emphasis countries placed on two major categories of performance: science knowledge and inquiry skills. Achieve then characterized the relative cognitive demand of performances in the knowledge category as *knowing, applying,* or *reasoning,* based on updated definitions in the TIMSS 2007 Framework[38] and performances in the inquiry category as *basic* or *advanced*. By adopting these sub-categories, Achieve was able to determine the relative emphasis countries place on higher-order thinking skills, i.e., *reasoning* and *advanced* inquiry.

The content experts found it relatively easy to distinguish knowledge expectations from inquiry performances because the standards statements include verbs such as *observe, compare*, *predict*, or *conduct an investigation, etc.,* that describe the actions the students are expected take in regard to the content. In most cases, countries made the inquiry learning intentions clear by including examples and descriptions of related laboratory activities.

KNOWLEDGE CATEGORY

Science content experts coded the cognitive dimension of performance expect: *Knowing, Applying,* and *Reasoning*. *Knowing* refers to the facts, procedures, and concepts students need to know; *Applying* focuses on their ability to apply their knowledge in straightforward scientific contexts. *Reasoning* is concerned with students' ability to analyze and interpret data; develop hypotheses; and design scientific investigations to test hypotheses, solve problems, develop explanations, draw conclusions, and/or extend their knowledge to new situations. (The sub-categories help reveal patterns; in practice the boundaries are not always distinct.)

Following are examples of countries' standards that illustrate three levels of cognitive demand.

Knowing

- *Canada* – Lower Secondary grade 9 Academic: *describe the characteristics of neutrons, protons, and electrons, including charge, location and relative mass.*
- *Hong Kong* – Upper Secondary Physics Curriculum and Assessment Guide (Secondary 4-6): *describe the meaning of inertia and its relationship to mass.*

Applying

- *Singapore* – Upper Primary: *Show an understanding of the effects of a force – A force can move a stationary object; A force can speed up, slow down or change the direction of motion; A force can stop a moving object; A force may change the shape of an object.*
- *Chinese Taipei* – Lower Secondary grades 7-9: *explain the difference between atoms and molecules in components and their properties.*
- *Finland* – Finland Elementary Science: *interpret physical maps, thematic maps, photographs, and statistics, and utilize news sources and information from data networks.*

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[38] Ina V.S. Mullis, Michael O. Martin, Graham J. Ruddock, Christine Y. O'Sullivan, Alka Arora, Ebru Erberber, TIMSS 2007 Assessment Frameworks (International Association for the Evaluation of Educational Achievement, Publisher: TIMSS & PIRLS International Study Center, Lynch School of Education, Boston College, 2005 IEA), 68-72.

Reasoning

- *Canada* – Canada Science, Grade 9: *analyse and interpret the effects of adding an identical load in series and in parallel in a simple circuit.*
- *Chinese Taipei* – Chinese Taipei, Required Physics: *Use molecular dynamics model to explain that pressure is caused by the moving molecules of gases heating the surface of containers.*

INQUIRY

Performance expectations for inquiry skills were coded as *Basic* or *Advanced*. Basic inquiry skills are foundational and consist of such proficiencies as gathering data by making observations and measurements, using laboratory equipment and simple computer applications, and carrying out routine experimental operations. Advanced inquiry skills build on the introductory skills to move to a higher level, shifting to an emphasis on skills required for carrying out independent investigations, as opposed to those needed for executing prescribed procedures.

Following are examples of countries' standards that illustrate basic versus advanced inquiry skills.

Basic

- *Japan* – Japan Primary: *Using weights and exploring the movement of objects by changing weights and speed of moving weights, and thus, enabling children to develop ideas about regularity in the movement of objects.*
- *Hong Kong* – Hong Kong Secondary 4-6 Chemistry: *demonstrate how to prepare solutions of a required concentration by dissolving a solid or diluting a concentrated solution.*

Advanced

- *Canada* – Canada Grade 9 Academic – Biology (Sustainable Ecosystems)*: plan and conduct an investigation, involving both inquiry and research, into how a human activity affects soil composition or soil fertility (e.g., changes to soil composition resulting from the use of different compostable materials, organic or inorganic fertilizers or pesticides), and extrapolating from the data and information gathered, explain the impact of this activity on the sustainability of terrestrial ecosystems.*

PATTERNS IN PERFORMANCE EXPECTATIONS

The overall breakdown in performance expectations for Primary through Upper Secondary is displayed in Table 13 below. The table shows an artificial distinction between the cognitive and inquiry processes – students of course, must *know*, *apply*, and *reason* as they carry out investigations or engage in design. However, these distinctions are useful in detecting patterns and emphases among the performance expectations called for in the countries' science standards.

Table 13: Assessing Overall Performance Expectations: Balance between Knowledge and Inquiry Categories in Primary through Upper Secondary

GRADE SPAN	LEVELS OF COGNITIVE DEMAND			% Knowledge	LEVELS OF INQUIRY SKILLS		% Inquiry Skills
	KNOWING	APPLYING	REASONING		BASIC INQUIRY	ADVANCED INQUIRY	
Primary	41%	23%	10%	**74%**	24%	2%	**26%**
Lower Secondary	36%	30%	14%	**80%**	16%	4%	**20%**
Upper Secondary Courses:							
Biology	49%	23%	16%	**88%**	8%	4%	**12%**
Chemistry	42%	31%	15%	**88%**	7%	4%	**11%**
Physics	40%	26%	16%	**82%**	13%	5%	**18%**
Earth Science	20%	21%	28%	**69%**	21%	9%	**30%**

Overall Findings

- The ratio of performances in the knowledge domain to those in the inquiry domain is approximately 3:1 at Primary; 4:1 at Lower Secondary; and varies substantially among Upper Secondary courses ranging from approximately 7:1 in Biology and Chemistry, to better than 2:1 in Earth and Space Science.
- In all courses, except Earth and Space Science, the Upper Secondary courses place relatively more emphasis on the knowledge domain in comparison with both Primary and Lower Secondary levels. (Only three countries have Standards for Earth Science at Upper Secondary, as compared to eight countries for the other subject areas.)
- The percentage of performances defined by the knowledge domain for Lower Secondary (80 percent) increases when compared with that found at the Primary level (74 percent). There is a corresponding decline in overall inquiry expectations at Lower Secondary compared with Primary, but a slight increase in advanced inquiry skills at Lower Secondary compared with Primary.
- Biology and Chemistry courses give much more emphasis to knowledge performances than inquiry, a ratio of approximately 8:1. In contrast, Physics places less emphasis on knowledge as compared to inquiry, a ratio of 4.5:1.

Emphases in Levels of Cognitive Demand and Inquiry

When comparing the proportionate levels of cognitive demand at Primary and Lower Secondary with that targeted by the TIMSS 2007 Science Assessment, the international averages fall considerably short of the assessment targets for *Reasoning*, the highest level of demand.

Figure 2: Target Percentages of the TIMSS 2007 Science Assessment Devoted to Cognitive Domain at Fourth and Eighth Grades [Exhibit 6 (excerpt)[39]]

Cognitive Domains	Percentages	
	Fourth Grade	Eighth Grade
Knowing	40%	30%
Applying	35%	35%
Reasoning	25%	35%

Findings: *Levels of Cognitive Demand*

- Although *knowing* is the predominant level of cognitive demand at all levels of schooling, in progressing from the Primary to the Lower Secondary countries begin to place more emphasis on *applying* and *reasoning,* as the data in Table 13 show.
- At the Upper Secondary level, Earth and Space Science has a greater emphasis on the levels of cognitive demand, as compared with the other disciplines. *Reasoning* registers the highest proportion of performance expectations, followed by *knowing*, then *applying*. (As noted above, only three countries have Earth and Space Science standards for Upper Secondary, as compared with eight countries in the remaining subject areas.)

Findings: *Levels of Inquiry*

- More attention is given to inquiry at the Primary (26 percent) than at the Lower Secondary level 20 percent), although Lower Secondary standards give slightly more attention to advanced inquiry skills.
- There is less attention to inquiry in at the Upper Secondary level than at the Primary and Lower Secondary levels. This finding may reflect the tension between the desire to have students engage in scientific inquiry and concern for coverage in Upper Secondary courses.40
- Countries place more emphasis on advanced inquiry skills in both lower and Upper Secondary grade spans than in Primary grades
- Upper Secondary subject-specific courses give more attention to students' advanced inquiry skills required for carrying out independent investigations than the Lower Secondary programs of study do.

[39] Ina V.S. Mullis, Michael O. Martin, Graham J. Ruddock, Christine Y. O'Sullivan, Alka Arora, Ebru Erberber, TIMSS 2007 Assessment Frameworks (International Association for the Evaluation of Educational Achievement, Publisher: TIMSS & PIRLS International Study Center, Lynch School of Education, Boston College, 2005 IEA), 42.

[40] ACT, Inc., COLLEGE READINESS, ACT National Curriculum Survey® 2005–2006 (ACT, Inc., 2007) revealed (on page 9) an expectations gap between high school and postsecondary instructors. "High school science teachers consistently rated science content as more important to student success than science process/inquiry skills" – a response at odds with that of postsecondary faculty and middle school teachers. Postsecondary faculty believed an in-depth focus on essential content and skills would better prepare students for success in college-level work than covering the range of content included in most state standards.

III. QUALITATIVE ANALYSIS

METHODOLOGY

Achieve conducted a preliminary review of all ten countries' standards and supporting documents on the basis of defined criteria designed to identify countries' standards that showed the most promise of being overall exemplars or had exemplary features worthy of emulation. Reviewers looked for evidence of a cohesive philosophy of science, an emphasis on over-arching ideas, a focus on content depth over breadth, a strong treatment of the nature of science and inquiry, inclusion of performance expectations, and the quality of supporting documents that enhance the standards.

Based on the preliminary review, Achieve selected five sets of standards – those of Canada, England, Hong Kong, Japan, and Singapore – for an in-depth qualitative review by content experts in Biology, Chemistry, and Physics. In Earth and Space Science, content experts reviewed standards from the three countries (Canada, Chinese Taipei, and Japan) that have Upper Secondary courses in this discipline.

Table 14: Countries included in Qualitative Analysis

Country	Preliminary Qualitative Review	In-Depth Qualitative Review: Biology, Chemistry & Physics	In-Depth Qualitative Review: Earth and Space Science
Canada [Ontario]	✓	✓	✓
Chinese Taipei	✓		✓
England	✓	✓	
Finland	✓		
Hong Kong	✓	✓	
Hungary	✓		
Ireland	✓		
Japan	✓	✓	✓
Singapore	✓	✓	
South Korea	✓		

Achieve formulated guiding questions, based in part on our long-established protocol for analyzing science standards, to provide content experts in biology, chemistry, physics and Earth and space science with a consistent method for their analysis of a diverse set of standards. For example, content experts were asked to respond to each of the following questions:

- *Coherence:* Are the standards based on an underlying conceptual framework that reflects the science as a unified discipline?
- *Focus:* Do the standards focus on the most important concepts on the major fields and do the expectations for a year or grade span appear to be manageable?
- *Rigor:* Are concepts developed in depth, is the level of cognitive demand of the standards appropriate to the grade level or grade span, are mathematical applications required, and do the standards require students to engage in laboratory or field investigations?

- *Progression:* Do the standards develop essential content with increasing depth from one grade level or grade span to the next?
- *Specificity:* Are the standards specific enough (at the right grain size) to guide instruction and are performance expectations tightly connected to the content knowledge required?
- *Clarity and accessibility:* Are the standards clear, logically organized, and user-friendly and are they are scientifically accurate?

Content experts were also asked to identify specific features of countries' standards that they considered exemplary – for example, the inclusion of aligned assessment guidelines – as well as to indicate weak points that reduce the effectiveness of the standards. Their findings are discussed in greater detail in the section that examines exemplary features of other countries' standards below. Before presenting the results of the analyses, it is useful to provide some background information regarding the way in which the ten countries structure and present their standards.

GENERAL CHARACTERISTICS

How Countries Organize Their Standards

Since each country has a unique historical, cultural, and economic context that shapes its educational system and standards, there is little reason to expect uniformity in the way countries organize, structure and articulate their national standards.

Countries organize their Primary and Lower Secondary standards in different ways. Achieve found that only two countries, Canada and South Korea, detail grade-level standards for grades 1-10; one country, Japan, has a blended approach with grade-level standards in the Primary grades and grade spans in the Lower Secondary grades; the remaining seven countries organize their standards in grade spans. Notably, two of the ten countries included in this study, Japan and Singapore, delay science instruction until grade 3. Three countries, Chinese Taipei, Finland, and Hong Kong begin discipline-based courses at grade 9, whereas the remaining countries do so at grade 10.

At the Upper Secondary level, countries have developed standards for discipline-based courses. Achieve's analysis includes eight countries' standards for Biology, Chemistry, and Physics (akin to the content of high school courses in the United States).[41] Only three countries offer similar courses in Earth and Space Science, and the corresponding standards are included in the analysis. For more information on the specific courses and standards documents included in this analysis, please see Appendix 2.

[41] Achieve's analysis includes discipline-based courses at the Upper Secondary level from neither Hungary nor South Korea as adequate English translations were not obtainable.

Table 15: Grade Spans and Courses for All Countries, Grades 1-12

<table>
<tr><th rowspan="2">COUNTRIES</th><th colspan="10">GRADES OR GRADE SPANS IN PRIMARY AND LOWER SECONDARY</th><th colspan="4">UPPER SECONDARY COURSES</th></tr>
<tr><th>Grade 1</th><th>Grade 2</th><th>Grade 3</th><th>Grade 4</th><th>Grade 5</th><th>Grade 6</th><th>Grade 7</th><th>Grade 8</th><th>Grade 9</th><th>Grade 10</th><th>Biology</th><th>Chemistry</th><th>Physics</th><th>Earth and Space Science</th></tr>
<tr><td>Canada</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>Chinese Taipei</td><td colspan="2">✓</td><td colspan="2">✓</td><td colspan="2">✓</td><td colspan="3">✓</td><td></td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>England</td><td colspan="2">✓</td><td colspan="4">✓</td><td colspan="3">✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td></td></tr>
<tr><td>Finland[1]</td><td colspan="4">✓</td><td colspan="2">✓</td><td colspan="3">✓</td><td></td><td>✓</td><td>✓</td><td>✓</td><td></td></tr>
<tr><td>Hong Kong</td><td colspan="3">✓</td><td colspan="3">✓</td><td colspan="3">✓</td><td></td><td>✓</td><td>✓</td><td>✓</td><td></td></tr>
<tr><td>Hungary</td><td colspan="4">✓</td><td colspan="2">✓</td><td colspan="2">✓</td><td colspan="2">✓</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Ireland</td><td colspan="2">✓</td><td colspan="2">✓</td><td colspan="2">✓</td><td colspan="4">✓</td><td>✓</td><td>✓</td><td>✓</td><td></td></tr>
<tr><td>Japan[2]</td><td colspan="2"></td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td colspan="3">✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>Singapore</td><td colspan="2"></td><td colspan="2">✓</td><td colspan="2">✓</td><td colspan="4">✓</td><td>✓</td><td>✓</td><td>✓</td><td></td></tr>
<tr><td>South Korea</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td></td><td></td><td></td><td></td></tr>
</table>

[1] Earth and Space Science content coded as part of the required *Geography* course
[2] Lower Secondary grades are organized into "First" and "Second" fields rather than grades

The fact that the countries analyzed organize their standards in grade levels or spans that terminate at the end of Lower Secondary, prior to students enrolling in discipline-specific courses, enabled Achieve to examine the science expectations that countries have for all students. These standards include content from each scientific discipline – as well as cross-cutting content – at each grade level or grade span, and provide a view of how countries define scientific literacy.

An obvious difference between the countries analyzed and the United States is that seven countries require participation in an integrated science program – life, physical, earth science, and cross-cutting content – through grade 10. Three countries have integrated science programs through grade 9. This pattern contrasts somewhat with the approach common in the United States, where students typically begin to take discipline-specific courses after grade 8 or 9. Students in other countries tend to have one or two years of general science instruction, beyond what their American peers receive, which allows them to build a stronger foundation in scientific literacy before enrolling in discipline-specific courses at the Upper Secondary level.

How Countries Structure Their Standards

The conceptual framework that underlies a country's standards has a considerable effect on their overall coherence and focus. Achieve found that the architecture countries use to structure their standards varies but can generally be characterized as either based primarily on key concepts in the major fields of the life, physical, and earth sciences or on foundational scientific themes (often referred to outside of this report as *"big"* ideas, these concepts include, for example, the idea that nature is composed of many interrelated systems).

While all ten countries included in this study have integrated standards in the Primary and Lower Secondary grade spans, eight of them generally organize their Primary and Lower Secondary standards based on core concepts in Biology, Chemistry, Physics, and Earth and Space Science. These countries also address a variety of cross-cutting ideas in their standards at all grade spans, including in their standards for Upper Secondary discipline-specific courses. However, these cross-cutting ideas are subsidiary to core concepts rooted in the disciplines.

In contrast, two countries, Singapore and Canada, structure their standards on foundational scientific themes common to all of the sciences – rather than by the disciplines of Biology, Chemistry, Physics, and Earth and Space Science. An architecture based on foundational themes, as opposed to one based on a "silo" approach to the disciplines, seems to offer an important advantage in terms of coherence and focus. A conceptual framework based on powerful themes provides a matrix for developing a strong story line that can help teachers and students make sense of seemingly disconnected content within and across years of instruction and impart an underlying coherence to the curriculum. A theme-based approach also provides a decision rule for selecting among the many concepts in the core disciplines that could potentially be included in a set of standards.

Singapore and Canada's approaches differ somewhat from one another in execution. Singapore organizes its standards for Primary through Lower Secondary (grades 3-10) around themes that encompass a core body of life and physical science concepts. Four themes – *Diversity*, *Systems*, *Energy*, and *Interaction* are common to both Primary and Lower Secondary. An additional theme, *Cycles*, appears only in Primary, while *Measurement* and *Science and Technology* appear only in Lower Secondary. (*Systems* expands at Lower Secondary to include *Models*.)

Canada structures its K-8 Science and Technology Standards around six "fundamental concepts:" *Matter*; *Energy*; *Systems and Interactions*; *Structure and Function*; *Sustainability and Stewardship*; and *Change and Continuity*. Both countries overlap in their selection of *Systems, Energy,* and *Interactions* as crossover ideas. While Canada shifts to a more discipline-based structure in Lower Secondary (grades 9 and 10) – centering on Biology, Chemistry, Earth and Space Science, and Physics, along with scientific investigation skills and career exploration – the standards continue to be linked to the fundamental concepts carried over from the lower grades.

Foundational scientific themes provide Canada and Singapore with the opportunity to build a spiral curriculum that reflects the inter-connectivity of all fields of science and the unity of science taken as a whole. Singapore describes the approach this way:

> *The Lower Secondary Science Syllabus is essentially a continuation and further development of the Primary Science Syllabus. It is also a bridge to, and a foundation for, the pursuit of scientific studies at Upper Secondary levels.*[42]

Like Singapore, Canada is clear about its intent:

> *As students progress through the curriculum from Grades 1 to 12, they extend and deepen their understanding of these fundamental concepts and learn to apply their understanding with increasing sophistication.*[43]

The samples below show how the two countries organize their standards. The first is an excerpt from Singapore's standards for *Interactions*. (See Appendix 4 for additional detail.)

[42] Singapore, Science Syllabus Lower Secondary Express/Normal (Academic) (Curriculum Planning & Development Division 2007), Preamble.
[43] Canada, Ontario, The Ontario Curriculum, Grades 1-8 Science and Technology (Queen's Printer for Ontario, 2007), 5.

Figure 3: Singapore Standards Format

<table>
<tr><th>Theme: Interactions</th><th colspan="2">Key Inquiry questions in Interactions include:</th></tr>
<tr><td>Students should appreciate that there are interactions between the living world and the environment at various levels: interactions, which occur within an organism; between organisms; and between organisms and the environment. There are also interactions between forces and objects, and energy and matter.</td><td colspan="2">• How does knowledge of interactions between and within systems help Man better understand his environment?
• What are the interactions between physical phenomena and life processes?</td></tr>
<tr><th colspan="3">Learning Outcomes</th></tr>
<tr><th>Knowledge, Understanding and Application</th><th>Skills and Processes</th><th>Ethics and Attitudes</th></tr>
<tr><td>Interaction of forces & energy -
Concept of force & pressure
• describe the effects of forces:
• on the state of rest or motion of a body
• on the size and shape of a body
• use the Newton as the S.I. unit of force
• …</td><td>• use a spring balance as one of the ways to measure force
• communicate their understanding of forces and justify their answers to questions on forces with reasons …</td><td>• show an appreciation of scientific attitudes such as curiosity, objectivity and perseverance in making careful observation and experimentation on force and its related concepts …</td></tr>
</table>

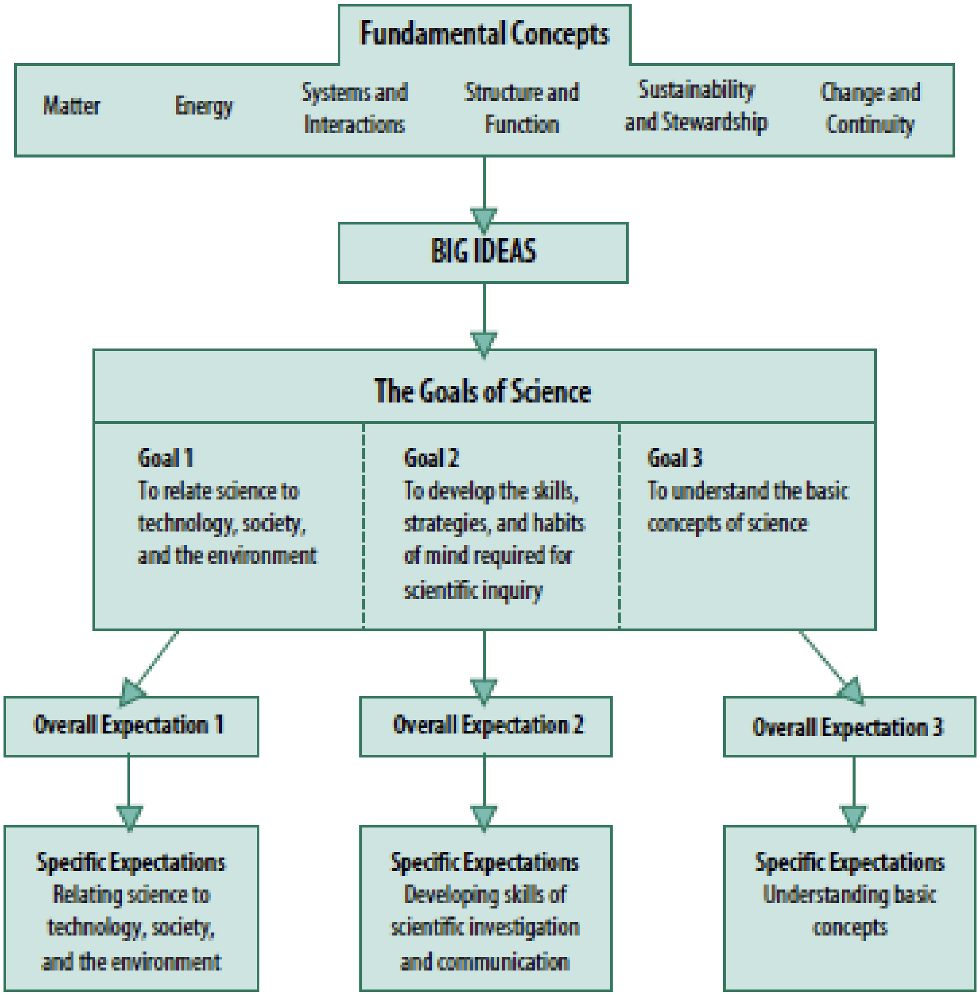
The discussion and excerpts from Canada's Grades 9 & 10 Science[44] curriculum below illustrate how Canada develops an overall expectation and aligned specific expectations related to *Earth and Space Science: Climate Change*.

> *"Big ideas" are the broad, important understandings that students should retain long after they have forgotten many of the details of what they have studied in the classroom. They are the understandings that contribute to scientific literacy. The big ideas that students can take away from each course in this curriculum relate to some aspect of the fundamental concepts described in the preceding section. A list of the big ideas students need to understand appears at the start of every course in this document.*
>
> *Developing a deeper understanding of the big ideas requires students to understand basic concepts, develop inquiry and problem-solving skills, and connect these concepts and skills to the world beyond the classroom. Teachers can help students gain such understanding by connecting learning based on the overall and specific expectations and the criteria in the achievement chart to the big ideas that relate to each course.*

The relationship between the fundamental concepts, big ideas, the goals of the science program, and the overall and specific expectations is outlined in the figure that follows.[45]

[44] Canada, Ontario, The Ontario Curriculum, Grades 9 & 10 Science – 2008 (Queen's Printer for Ontario, 2008), 78.
[45] Ibid, 6.

Figure 4a: Canada Science Standards Format



An excerpt from "Overall Expectation 1" is shown in the figure below describing its relationship to an example of a specific expectation within the *Earth and Space Science: Climate Change,* strand (D) in Canada's Grade 10 Academic course, and the role that sample issues and sample questions play in elucidating a specific expectation.

Figure 4b: Canada Science Standards Expectations and Sample Issues

Overall Expectations – Numbering indicates strand (in this case *Earth and Space Science* to which it belongs)

OVERALL EXPECTATIONS

By the end of this course, students will:

D1. analyse some of the effects of climate change around the world, and assess the effectiveness of initiatives that attempt to address the issue of climate change;

D2. investigate various natural and human factors that influence Earth's climate and climate change;

D3. demonstrate an understanding of natural and human factors, including the greenhouse effect, that influence Earth's climate and contribute to climate change.

D1 numbered subheading links to Overall Expectation D1 and Goal 1 (in above figure)

Specific Expectations for D1 = D1.1 and D1.2

SPECIFIC EXPECTATIONS

D1. Relating Science to Technology, Society, and the Environment

By the end of this course, students will:

D1.1 analyse current and/or potential effects, both positive and negative, of climate change on human activity and natural systems (e.g., loss of habitat for Arctic mammals such as polar bears and loss of traditional lifestyles for Inuit as Arctic ice shrinks; famine as arable land is lost to desertification; an increase in water-borne disease and human resettlement as coastal lands are flooded; expansion of the growing season in some regions) [AI, C]

Sample Issues and Questions

Sample issue: Scientists are researching changes in climate patterns as possible contributing factors to an increase in the number of smog days in Ontario and elsewhere in Canada. As the air quality worsens, people may curtail their outdoor activities, and those with respiratory problems may require medical attention, increasing health care costs.

Sample questions: How have recent extreme weather events such as heat waves in Europe or drought in southern Africa affected habitats in these regions? How might predicted changes to global temperature and precipitation affect agriculture in Ontario, Canada, or different areas around the world? How might the continuing reduction of the polar ice cap influence domestic and international transportation and shipping?

D1.2 assess, on the basis of research, the effectiveness of some current individual, regional, national, or international initiatives that address the issue of climate change (e.g., Drive Clean, ENERGY STAR, federal and provincial government rebates for retrofitting older buildings to be more energy efficient, carbon offset programs, community tree-planting programs, municipal recycling programs, Intergovernmental Panel on Climate Change [IPCC]), and propose a further course of action related to one of these initiatives [PR, AI, C]

Sample issue: Governments and industry have created rebates or tax cuts to encourage consumers to replace their old appliances with efficient ENERGY STAR appliances. However, such initiatives do not take into account the resources used to create the new products or the problems associated with the disposal of old appliances.

Sample questions: What type of recycling and composting programs are in place in your community? What proportion of locally generated garbage do they divert from landfill sites? How could they be improved? What is the purpose of carbon offset credits? Do they achieve that purpose? Why or why not?

The ***abbreviations in square brackets*** following many specific expectations link the expectation to one or more of the *four broad areas of scientific investigation skills:* Initiating and Planning (IP), Performing and Recording (PR), Analysing and Interpreting (AI), and Communication (C)

The organizational features evident in these sample standards show that both countries also lay out their standards in a way that fully develops the links between content and skills. Thus, it is instructive to compare the development of a similar concept in an interdisciplinary approach versus a discipline-based approach. Tracing the pathways that Singapore, Canada, and Finland follow in developing the concept of energy, shows that Singapore and Canada situate energy in a web of interrelated ideas, whereas Finland presents energy more as an isolated topic, linked primarily to electricity. (Appendix 5 describes how the concepts of *heat and electrical energy* are framed and developed in these three countries.)

How Countries Articulate Their Standards

Countries' standards statements vary greatly in grain size and specificity. For example, consider Hong Kong's Learning Objective for Primary 4-6 concerning The Material World:

> *To distinguish between changes that cannot be easily reversed and those that can.*

In contrast, Canada devotes two grade 5 standards to the same concept:

> *Describe physical changes in matter as changes that are reversible (e.g., a melted ice cube can be re-frozen; a bottle of frozen water can be thawed to a liquid state again; water vapor that has condensed on a cold window can evaporate into a vaporous state again; water from a puddle that has evaporated will fall to the ground as rain);* and
>
> *Describe chemical changes in matter that are irreversible (e.g., when the chrome on a bicycle rusts, it can never go back to being chrome; when an egg is boiled it can never go back to being a raw egg.)*

It may be that countries' standards that appear to be imprecise, and offer descriptions at a fairly large grain size, are supported by explicit instructional guides that were not available to Achieve in English translations. However, it would seem that Canada's model has much to recommend it because it includes the incorporation of everyday examples that provide a clear context for particular content. This is illustrated by Canada's *"Sample issues"* that accompany specific learning expectations shown in the figure below:

Figure 4c: Canada's "Sample Issues" Excerpt

GRADE 4 | **UNDERSTANDING STRUCTURES AND MECHANISMS**[46]
PULLEYS AND GEARS
SPECIFIC EXPECTATIONS
1. Relating Science and Technology to Society and the Environment
By the end of grade 4, students will:
1.1 assess the impact of pulley systems and gear systems on daily life
Sample issues: Elevators and other lifting devices use pulley and gear systems; they allow people with physical challenges to have equal access to all floors of a building. Bicycles use gears; they provide us with transportation and exercise. Snowmobiles, VCRs, and joysticks use pulleys and/or gears; they provide us with leisure activities. Clothes dryers and clotheslines, sewing machines, and windshield wipers on cars and trucks use pulleys and/or gears. However, many of these mechanisms require power to operate.

[46] Canada, Ontario, The Ontario Curriculum, Grades 1-8 Science and Technology (Queen's Printer for Ontario, 2007), 78.

A significant advantage of including sample issues is that it grounds the expectations for students with respect to the relationship of science, technology, and society. In Achieve's experience reviewing state science standards, standards related to issues about science, technology, and society tend to be amorphous, written at a high level of generality and challenging to assess.

IN-DEPTH ANALYSIS OF FIVE COUNTRIES – SEARCH FOR EXEMPLARY FEATURES

After developing an overview of the standards of all ten countries, Achieve selected standards from Canada, England, Hong Kong, Japan, and Singapore for an in-depth review by content experts in Biology, Chemistry, and Physics. (In Earth and Space Science experts reviewed standards from the three countries (Chinese Taipei, Japan, and Canada) that have Upper Secondary courses in this discipline.) The goal for this phase of the analysis was to identify a country whose standards could serve as an overall exemplar and/or to identify exemplary features across all countries that could be highlighted for the consideration of the developers of the U.S. science standards.

Achieve asked the content experts to review the five countries' standards based on criteria Achieve has developed for evaluating science standards – coherence, focus, rigor, progression, specificity, and clarity and accessibility. They were also asked to take note of salient features and shortcomings that could be helpful in informing the NRC framework and next-generation standards.

In the end, Achieve content experts were unable to single out one country whose standards could serve as an exemplar for Primary through Upper Secondary in the four major disciplines. However, they found many features compelling and worthy of consideration in thinking through a conceptual framework and developing next-generation science standards.

COHERENCE

The content experts examined the five countries' standards for evidence of an underlying conceptual framework that reflects the nature of science, and in particular, to determine if a given country's framework reflected the NRC's vision, as articulated in *Taking Science to School* (2007). The NRC drew on extensive research studies to define what it means to be proficient in science and developed a new framework that "*rests on a view of science as both a body of knowledge and an evidence-based, model-building enterprise that continually extends, refines and revises knowledge.*" It thus offers a unified, succinct vision of modern science, leaving no doubt that science content and processes are inextricably linked. The NRC identifies four intertwined strands that explain what it means for students to be proficient.

The content experts looked for evidence of the four strands in each country's set of standards. They found that while the four strands are addressed at least partially by all five countries included in the detailed analysis, countries generally do not describe how the science practices are related to one another or develop them as comprehensively as does the NRC.

In general, none of the other countries address the strands in a way that is as conceptually and pedagogically coherent as the NRC *Taking Science to School* presentation. Below is a summary of Primary observations about the coherence of countries' standards based on their attention to the elements described in the four strands.

> <u>Strand 1</u> calls for students to *know, use and interpret scientific explanations of the natural world*. A general strength of the five countries' standards is that all expect students not only to recall facts, principles, laws, and theories but also to apply their knowledge. England, for example, further specifies that students are to give their own explanations of phenomena.

Strand 2 is concerned with students developing the ability to *generate and evaluate scientific evidence and explanations* by (a) relying on empirical evidence, (b) modeling, and (c) acquiring skills in inquiry.

(a) Relying on Empirical Evidence

This calls for students to back up claims with evidence appear in some countries' standards, but this element is not a consistent thread in all. For example:

- *England* emphasizes evidence-based reasoning in its standards and assessment targets for scientific inquiry. The standards pay careful attention to what "doing science" means in student terms and what evidence suffices to verify that students have attained desired competencies.
- *Canada's* Upper Secondary science standards include multiple references to the need for students to back up claims in secondary standards, although there are few instances of discussion of evidence in its standards for grades 1-8.
- *Singapore* includes the question "*What conclusions can I make based on my observations and evidence collected?*"[47] but this element is not a pervasive theme.

(b) Modeling

Models are referenced frequently in most countries' standards, especially in Upper Secondary. But *modeling* is not generally developed in a cohesive way across all grade spans in the standards of any of the countries – with the notable exception of *Canada*.

- A representative example is *Finland's* call in its Lower Secondary standards for students to *learn concepts and models that describe the chemical bonds and structure of matter.*[48]
- *Singapore* provides a strong framework for its treatment of models at Lower Secondary, where it initially introduces the concept as: *Students should appreciate that models are simplified representations of phenomena*. *These models are constructed to facilitate understanding of the phenomena. There are three types of models in the learning of science, namely, physical conceptual and mathematical.*[49] However, Singapore does not seem to develop this approach systematically across its standards.

(c) Acquiring Skills in Inquiry

The part of Strand 2 most fully developed by all five countries is inquiry skills, which are featured at the Primary and Lower Secondary levels, and to a lesser extent in the Upper Secondary, discipline-specific courses. Though all of the countries address laboratory investigations, there are important differences among the five countries with regard to how they envision inquiry:

- *Hong Kong* highlights inquiry as one of three major areas of its curriculum and urges teachers to devise experiments in which students need to design the procedure – not just follow instructions. Hong Kong also includes a description of how to reframe "cookbook" laboratory activities into more engaging, more cognitively demanding investigations. At the Upper Secondary level, most laboratory activities are low-level and confirmatory. Nevertheless, the curriculum and assessment guides that accompany the country's Upper Secondary courses

[47] Singapore, Science Syllabus Lower Secondary Express/Normal (Academic) (Ministry of Education, Curriculum Planning & Development Division, 2007), 19.
[48] Finland, National Core Curriculum for Basic Education (2004) (Finnish National Board of Education, 2004), 192.
[49] Singapore, Science Syllabus Lower Secondary Express/Normal (Academic) (Ministry of Education, Curriculum Planning & Development Division, 2007), 27.

allocate time for independent investigations. In Biology, 20 hours are set aside for "*arranging large-scale or cross-topic investigations to provide opportunities for students to develop the full range of skills and appreciate the nature of science.*"[50] Chemistry lists a 20-hour investigative study that is well designed and worthy of emulation (for more details see Appendix 6), while Physics includes a 16-hour investigative study that students are expected to design themselves.

- *Japan* stresses the importance of scientific inquiry, and has similar requirements to Hong Kong in that Chemistry II, Physics II, and Earth/Space Science II all call for students to conduct original research projects.
- *England* embeds performance expectations in upper Primary and interweaves them with content in Lower and Upper Secondary.
- *Canada* includes, at each grade level for each strand, separate investigative expectations that encompass field studies, technological designs, and other research, all of which are connected to the basic concepts in the strand. All the disciplines include throughout their standards the expectation that all students *…develop the skills, strategies, and habits of mind required for scientific inquiry and technological problem solving* accompanied by specific investigations and/or open-ended challenge.
- *Singapore's* standards call for laboratory investigations, but many are routine.

Strand 3 is concerned with students *understanding the nature and development of scientific knowledge*, including the idea that *scientific knowledge is a particular kind of knowledge with its own sources, justifications and uncertainties*.[51] Achieve did not find consistent emphasis in any of the countries' standards on presenting "*science as a process of building theories and models, checking them for internal consistency and coherence, and testing them empirically.*"[52] It is also the case that countries generally do not place much emphasis on turning points in the history of science – points in time when previous conceptions or major theories were substantially altered. It may be that Strand 3 is more fully represented in curriculum guides, especially areas concerned with the history of science and the development of major theories over time, than in the standards. The following exceptions should be noted:

- *Canada* makes specific mention of the need for students to know evidence for major theories, such as the "Big Bang," and the age of the Earth.
- *Hong Kong's* Upper Secondary standards for Biology call for students to *formulate and revise scientific explanations and models using logic and evidence (e.g. use of fossil records as evidence for evolution).*
- *Canada*, *England*, and *Hong Kong* include specific standards indicating that it is important for students to reflect on changes in their own understanding of science.

Strand 4 concerns the need for students to *participate productively in science*, to learn the language and the norms of argumentation in science. This strand is generally not well represented in countries' standards, except for the ability to communicate the results of investigations. There was

[50] Hong Kong, Science Education Key Learning Area Biology. Curriculum and Assessment Guide (Secondary 4 - 6) Curriculum Development Council and the Hong Kong Examinations and Assessment Authority, 2007), 26.
[51] Richard A. Duschl, Heidi A. Schweingruber, and Andrew W. Shouse, editors, Taking Science to School: Learning and Teaching Science in Grades K-8 (National Research Council, Committee on Science Learning, Kindergarten Through Eighth Grade. Board on Science Education, Center for Education, Division of Behavioral and Social Sciences and Education, Washington, DC: The National Academies Press, 2007), 37.
[52] Ibid, 182.

also less mention of the need for students to work in teams than we might expect, given that collaboration is such a common element in the modern workplace – with some exceptions. For example:

- *England* addresses the importance of students learning scientific argumentation skills.
- *Hong Kong* calls for students to develop specific collaboration skills.
- *Singapore* states that students should value working in a team as part of scientific inquiry.

FOCUS

The content experts examined the five countries' standards to determine to what degree the standards realized a strong focus by selecting important concepts and using them to limit the amount of content the standards address.

Canada and *Singapore*, as noted previously, achieve a strong focus by identifying half-dozen cross-disciplinary ideas that become the basis for selecting content. Both countries limit content to control manageability and center, for the most part, on important concepts, but the aptness of the choices varies across the disciplines. For example:

- All five countries included in the qualitative review limit the number of concepts that students are expected to learn each year in order to encourage in-depth learning. England, for example, gives priority to electrical energy and limits the treatment of force and motion – topics that traditionally receive considerable attention. Japan specifically cautions against including too much content, and Singapore devotes 15 percent of instructional time to "white space" to permit deeper exploration of topics. Hong Kong also restricts the number of topics, increasing depth of understanding with each succeeding treatment.
- *Canada's* Biology selections appear to be uneven. The concepts of ecosystems and the environment are well developed in grades 1-9, but no treatment of natural selection, extinction, or fossils is provided prior to grade 11. Cell theory is the basis of the grade 8 Biology content in Canada's standards, but the development of cell biology is weak (there is no mention of proteins or enzymes), as is the treatment of heredity. In light of these omissions, content experts raised the question of whether excessive attention is paid to taxonomy and classification. Similarly, in Earth and Space Science, no treatment of weather is provided. In contrast, the Chemistry standards in 1-8 provide a solid foundation for continuing study in grades 9 and 10 by targeting energy, macroscopic properties of materials and their interactions, states of matter, and physical and chemical changes.
- *Singapore's* standards present a somewhat different situation. Primary science instruction begins at grade 3 and targets central concepts: states of matter, light and shadows, and heat and temperature. The upper Primary standards build on and extend these concepts, emphasizing changes in states of matter, electrical circuits and conductivity, and forces and energy. Lower Secondary standards continue to build understanding of these concepts, but the treatment is relatively shallow. Content experts noted a steep rise in expectations in going from Lower Secondary standards to Upper Secondary courses.
- *Hong Kong's* standards document is also worth mentioning because it is atypical. In Primary and Lower Secondary, Hong Kong structures its standards in a non-traditional way. The organizing strands are a mix of six interrelated themes: Scientific Investigation, Life and Living, The Material World, Energy and Change, The Earth and Beyond, and Science, Technology, and Society, rather than a structure based on the major fields of science, favored by countries other than Canada

and Singapore. Learning objectives emphasize the practical aspects of science, highlighting the interrelationship of science, technology, and society.

RIGOR

Content experts also examined the rigor of countries' standards by examining how each dealt with the issue of cultivating depth of understanding, the level of cognitive demand in the context of the grade spans, the degree to which mathematical applications are included, and the way scientific inquiry is treated.

(a) Depth vs. Breadth

Recent research examining the relationship between the performance of college students in introductory science courses and the amount of content covered in their high school science courses concluded that "*students who reported covering at least one major topic in depth, for a month or longer, in high school were found to earn higher grades in college science than did students who reported no coverage in depth. Students reporting breadth in their high school course, covering all major topics, did not appear to have any advantage in Chemistry or Physics and a significant disadvantage in Biology.*"[53] The five countries in the qualitative review generally allowed for depth by constraining the amount of content included in the standards, as noted above under focus. Following are some illustrations of how other countries deal with the tradeoff between depth and breadth. In Hong Kong's Upper Secondary courses, for example, extensions illustrate what it means to go deeper.

- *Hong Kong* describes core understandings with regard to the ideal gas laws and Kinetic Theory. Students first learn that the kinetic theory of gases correlates temperature with the kinetic energy of gas molecules, and to interpret pressure in terms of the motion of gas molecules. For example, students are asked to *interpret temperature as a quantity associated with the average kinetic energy due to the random motion of molecules in a system*.

  In a subsequent section, student expectations regarding the Kinetic Theory are further elaborated:

  Kinetic Theory[54]
  - realise the random motion of molecules in a gas
  - realise the gas pressure resulted from molecular bombardment
  - interpret gas expansion in terms of molecular motion
  - state the assumptions of the kinetic model of an ideal gas
  - derive $pV = Nmc^2/3$
  - interpret temperature of an ideal gas using $K.E._{average} = 3RT/2N_A$
  - realise the condition that at high temperature and low pressure a real gas behaves as an ideal gas
  - solve problems involving kinetic theory

[53] Schwartz, M. S., Sadler, P. M., Sonnert, G. and Tai, R. H. "Depth versus breadth: How content coverage in high school science courses relates to later success in college science coursework" (Science Education, 93: 798–826. doi: 10.1002/sce.20328, 2009), 1.

[54] Hong Kong, Science Education Key Learning Area Physics. Curriculum and Assessment Guide (Secondary 4 - 6) (Curriculum Development Council and the Hong Kong Examinations and Assessment Authority, 2007), 19-20.

(b) Cognitive Demand of Performance Expectations.

The rigor of standards is most effectively and efficiently communicated when countries link content and performance expectations in each standard statement. The five sets of standards vary in their approaches.

- *Canada, Hong Kong,* and *Singapore* all assign performance expectations to each content statement, while Japan does not. The verbs countries use to describe the performances they expect of students also provide a window on the intellectual demand of their standards; Canada, Hong Kong, and Singapore include a range of verbs that challenge students at different cognitive levels.
- *England* has established attainment targets for the Primary and Lower Secondary grade spans that specify performance expectations with a rubric that defines characteristics of levels of performance on a scale of 1-8. The rubric uses high-demand cognitive verbs such as *plan*, *elect*, *communicate*, and *evaluate*.

(c) The Incorporation of Mathematics in Science Standards

Mathematics is the bedrock of science, technology and engineering – it is the ability to quantitatively describe and measure objects, events, and processes that makes mathematics and science so powerful in extending human knowledge. Moreover, because of the rapid and almost unimaginable increase in the power of computers, advances in science now depend routinely on techniques of mathematical models, remote imaging, data mining and probabilistic calculations that were unthinkable a decade ago. The math-science connection is not, however, obvious to students. How science standards address and incorporate mathematics can make a difference in how easily students develop quantitative habits of mind. The standards varied in the way Primary and Lower Secondary standards and Upper Secondary courses incorporated mathematics:

- *Primary and Lower Secondary Levels.* In general, the five countries incorporate minimal applications of mathematics in their Primary science standards, usually limiting demands to graphing. At the Lower Secondary level the picture shifts only slightly. England is more demanding than most in calling for students to apply formulas and make routine calculations – the overall level of demand is on par with or slightly below content expected in an introductory Algebra course. Canada, Singapore, and Hong Kong generally favor a qualitative approach and minimize applications of mathematics. However, Canada addresses quantitative applications in its investigation standards, calling for the application of formulas in the physical science strand. Japan does not specify mathematics applications, but a quantitative perspective is implied in its selection of topics, such as density, forces, relationship between current and voltage, and stoichiometric relationships in chemical equations.
- *Upper Secondary Levels.* The content experts noted a shift in mathematical applications in the Upper Secondary courses of two countries – Singapore and Hong Kong. Singapore's level of performance emphasizes qualitative explanations for most of grades 7-10, but in moving from Lower Secondary to Upper Secondary the syllabus standards become considerably more quantitative and challenging in Chemistry and Physics. Singapore's Upper Secondary Physics course requires understanding of Algebra, Geometry, and Trigonometry and often uses the term "show" to indicate that students must demonstrate how to derive mathematical relationships from other equations. See Appendix 7 for a description of Singapore's expectations in mathematics for its Upper Secondary Physics course.

In Hong Kong there is little application of mathematics required in Lower Secondary, but in Upper Secondary Physics, students are expected *to present concepts of physics in mathematical terms whenever appropriate.* Mathematics applications are rigorous and embedded in the content statements. For example, the unit *Force and motion* includes[55]:

***Addition and resolution of forces**:*

- *find the vector sum of coplanar forces graphically and algebraically*
- *resolve a force graphically and algebraically into components along two mutually perpendicular directions*

In Hong Kong's Upper Secondary Biology course, mathematics is included from the use of simple numbers (discuss the variation in the number of mitochondria in different tissues and cell types), to the employment of probabilities in genetics problems to the use of sampling methods in ecological studies problems.

Canada's Upper Secondary course in Earth and Space science calls for using graphs to learn about stars (H-R Diagram), conducting mathematics analysis of spectral data to determine surface temperature from peak wavelength using Wein's Law, determining motion using the Doppler effect, and investigating stellar distances using a numerical parallax. These applications are also integrated with the content rather than being placed in a separate section.

PROGRESSION

The content experts looked for evidence that countries' standards developed essential content with increasing depth from one grade level or grade span to the next. They often found the progression of content and skills to be uneven. In fact, conceptual disconnects were a major reason why none of the countries' standards proved to be an exemplar across the board from Primary through Upper Secondary. The following is a sample of the disjuncture content experts uncovered during their reviews.

- *Canada:* In general, progression is sensibly designed in incremental steps – specific expectations often suggest a "building up" strategy in keeping with the expressed intent of a spiral curriculum. For example, in Chemistry, development proceeds from representing substances and reactions in progressively different ways (basic nomenclature and word equations on through formulas and balancing symbolic equations). However, in other areas, such as cellular biology, conceptual development is weak.
- *England:* Comparisons of successive Key Stages reveals few instances of concepts being developed in greater depth from stage to stage, rather the successive stages introduce additional concepts under given topic headings. However, while the stages only occasionally flesh out learning progressions, England's Attainment Targets describe clearly the progressive steps in learning the concepts being taught, in addition to providing guidance for classroom assessment.
- *Hong Kong:* Evolution and genetics are included in Upper Secondary but do not build from earlier grades.
- *Japan:* While each grade span has organizing topics, there appears to be little connection between the topics of one grade span and those of another.
- *Singapore:* The groundwork for all of the topics in Physics and Chemistry is provided at the Primary level. These include materials, cycles, and interaction of forces & energy. Concepts

[55] Hong Kong, Science Education Key Learning Area Physics. Curriculum and Assessment Guide Secondary 4 - 6 (Curriculum Development Council and the Hong Kong Examinations and Assessment Authority, 2007), 36.

within these areas are further addressed at the Lower Secondary level, as would be expected in a spiral approach to curriculum. However, the content experts found a considerable gap between the content complexity in Lower Secondary Chemistry and Physics, as compared with that expected in Upper Secondary Chemistry and Physics.

SPECIFICITY

Specificity is an important criterion for judging standards as it affects rigor. If standards are vague or if performance expectations are not tightly connected to the content knowledge required, the level of rigor is difficult to discern. Here also, the standards vary.

- *Canada:* Expectations are thoroughly articulated and standards are quite clear – replete with examples that make expectations for students quite concrete. In general, the grain size (precision) of the standards is appropriate and consistent, although the standards in the science, technology, and society categories tend to be larger and more open-ended than those in the investigation and content sections.
- *England:* Primary statements (Key Stages 1 and 2) are specific with a consistent and reasonable grain size, but stages 3 and 4 are less so. England's specifications for its secondary courses Science and Additional Science are precise.
- *Hong Kong:* The precision of the standards statements in the curriculum guide for Primary through Lower Secondary is quite uneven: some of the objectives are specific, but many are vague. At higher levels, the grain size is more appropriately specific, as is of the case in most countries' standards. For example, the Physics standards for Lower Secondary feature clear, concise performances as illustrated in the excerpt[56] below:

  Transfer processes

  conduction, convection and radiation

  - *<u>identify</u> the means of energy transfer in terms of conduction, convection and radiation*
  - *<u>interpret</u> energy transfer by conduction in terms of molecular motion*
  - *<u>realise</u> the emission of infra-red radiation by hot objects*
  - *<u>determine</u> the factors affecting the emission and absorption of radiation*

  At Upper Secondary Hong Kong provides detailed instructional guides in Biology, Chemistry and Physics to support the alignment of curriculum, pedagogy and assessment. These guides are unique among the countries examined in that they give recommended time allocations for each major unit. Appendix 8 includes an excerpt from Hong Kong's Guide for Secondary Chemistry that shows the nature of the instructional support materials. It also includes one compulsory chemistry unit, *The Microscopic World, which lists the major topics that comprise the unit and precise expectations for student performance.*
- *Japan*: In contrast to most other countries, where the standards become more precise in Upper Secondary, Japan's standards statements tend to become more general across the grade spans. However, Japan provides guidance for teachers by including sections entitled *Points for consideration in dealing with contents* that expand instructional expectations for each standard statement.

[56] Ibid, 29.

- *Singapore*: The grain size across grades 3-6 is irregular. For example, "*Recognize that good conductors of electricity are generally good conductors of heat" is specific whereas "Recognize the importance of the water cycle*" is comparatively diffuse.

CLARITY AND ACCESSIBILITY

Standards are meant to guide instruction. Thus, they need to be clear, logically organized, user-friendly, and scientifically accurate. The clarity and accessibility of a country's standards are principally a function of their underlying structure, language choice, and formatting decisions. Judging the clarity and accessibility of standards translated from other languages presents special challenges. With that caveat in mind, reviewers found standards from Canada, England, Hong Kong, and Singapore to be well organized and clearly written.

ADDITIONAL EXEMPLARY FEATURES

Beyond findings that relate to the six criteria (coherence, focus, rigor, progression, specificity, and clarity and accessibility) content experts identified additional exemplary features of countries worthy of mention:

- *Use of Multiple Examples:* Multiple robust examples in content and performance expectations enhance instruction and support specificity and clarity. Canada's incorporation of *sample issues, sample questions,* and embedded content *examples* help learners connect science concepts with everyday experiences.

- *Connecting Standards to Assessment*: Standards that establish a meaningful connection to assessment call attention to the ultimate goal of raising student achievement. Canada, England, and Hong Kong all make a special effort to show how their standards and assessments are aligned. Approaches vary considerably, but all three countries make solid links between the content they expect students to learn and how that learning will be evaluated. England's Attainment Targets provide rubrics for teachers to use in assessing students' performance levels and their understanding of content for each topic, as well as for investigation skills, thus providing consistent instructional guidance. Hong Kong provides detailed specifications of measurement standards. Ontario takes assessment guidelines to another level in designing a set of assessment tasks and scoring rubrics, and publishing related samples of genuine student work that illustrate what level of performance is sufficient to attain the various levels of proficiency. (See Appendix 9 for additional detail).

- *Engineering/Technological Design*: Canada's standards for grades 1-8 include a separate, but parallel matrix for *Scientific Inquiry/Research Skills* and for *Technological Problem-Solving Skills* that describes a full continuum of stages of proficiency. These matrices chart the extent of student learning from *beginning* to *exploring* to *emerging* to *competent* in four key areas: 1) Initiating and Planning; 2) Performing and Recording; 3) Analyzing and Interpreting and Communication, common to Inquiry and Technological Problem-Solving Skills. (Appendix 10 contains a side-by-side excerpt that highlights commonalities in the inquiry and design process for two stages in the continuum.)

- *Model-Building:* Canada[57] provides a comprehensive treatment of models and model-building, including performances that require students to build, design, and test models in grades 1-8.

  For example, starting in grade 1, students are expected to:

[57] Canada, Ontario, The Ontario Curriculum, Grades 1-8 Science and Technology (Queen's Printer for Ontario, 2007).

- Use technological problem-solving skills, and knowledge acquired from previous investigations, to design, build, and test a structure for a specific purpose (e.g., a tent, a model of a swing set or other playground equipment, a bird feeder, a wigwam for people who need to move throughout the year)

In grade 7 student expectations move beyond the *Engineering/Technological Design* problem-solving processes of designing, building, and testing physical models by introducing the idea of scientific models for explaining phenomena or supporting theories. For instance, students learn about the scientific model of the *particle theory* to describe the particulate nature of matter thereby providing students with a conceptual basis for learning this content.

In Ontario's Lower Secondary[58] grades 9-10 students focus on both physical models and science conceptual models as they are expected to:

- construct molecular models to represent simple molecules (e.g., O_2, CO_2, H_2O, NH_3, CH_4)
- explain how different atomic models evolved as a result of experimental evidence (e.g., how the Thomson model of the atom changed as a result of the Rutherford gold-foil experiment)
- describe patterns in the arrangements of electrons in the first 20 elements of the periodic table, using the Bohr-Rutherford model
- design and build a model to illustrate the natural greenhouse effect, and use the model to explain the anthropogenic greenhouse effect using the Bohr-Rutherford model

In Upper Secondary[59], student expectations concerning models grows more sophisticated in that students are expected to use models not only to represent scientific phenomena, but to predict the structure of particles in nature, and to analyze scientific theories. For example, in Chemistry students are expected to:

- predict the shapes of simple molecules and ions (e.g., CH_4, SO_3, O_2, H_2O, NH_4^+), using the valence shell electron pair repulsion (VSEPR) model, and draw diagrams to represent their molecular shapes
- explain how experimental observations and inferences made by Ernest Rutherford and Niels Bohr contributed to the development of the planetary model of the hydrogen atom

In Earth science, students are expected to:

- design and build a model to represent radioactive decay and the concept of half-life determination

In Physics, students are expected to:

- identify, and compare the properties of, fundamental forces that are associated with different theories and models of physics (e.g., the theory of general relativity and the standard model of particle physics) analyse, with reference to quantum mechanics and relativity, how the introduction of new conceptual models and theories can influence and/or change scientific thought and lead to the development of new technologies

Scientific model-building is clearly an important tool of science conceptualization and theorizing. Ontario shows the way for further development of the new U.S. science standards in this area.

- *Inclusion Guidelines:* England's standards contain a section called *Inclusion: providing learning opportunities for all pupils*, that specifically addresses students with special educational needs, including but not limited to students with disabilities and students who are learning English as an additional language. Hong Kong also addresses the need to accommodate students of exceptional ability and expects teachers to adapt the curriculum *to suit students of different*

58 Canada, Ontario, The Ontario Curriculum, Grades 9 & 10 Science – 2008 (Queen's Printer for Ontario, 2008)
59 Canada, Ontario, The Ontario Curriculum, Grades 11 & 12 Science – 2008 (Revised) (Queen's Printer for Ontario, 2008)

needs, interests, abilities, experiences, and learning styles. Teachers can develop themes to cover the core elements for students of average abilities, and provide extension themes and activities for student of higher ability. Hong Kong includes specific extensions in the content standards for higher-ability students.

SHORTCOMINGS IN STANDARDS DOCUMENTS

Clearly, the five countries' standards have much to recommend them. However, Achieve also found weaknesses in several areas as described below. These present opportunities for the developers of the NRC framework and new science standards to carve out a fresh vision for science education.

- *Incorporation of Mathematics*: The importance of integrating mathematics with science standards has long been raised as a central issue by both AAAS and the NRC. Recent research has revealed, "*High-school mathematics carries significant cross-subject benefit (e.g., students who take high-school calculus average better grades in college science than those who stop at pre-calculus).*"[60] This is an area in which none of the countries has been completely successful.
- *Evidence-based Inquiry*: The five countries do not generally call for students to consistently focus on evidence. This area is an instance of where an exemplar is found in U.S. standards. The recently revised College Board Standards call attention to and consistently incorporate science practices that focus on *establishing lines of evidence, using the evidence to substantiate claims, to develop and refine testable explanations, and to make predictions about natural phenomena*.[61]
- *Chemistry Foundation for Concepts in Modern Biology*: The five countries' Primary and Lower Secondary standards in Biology do not appear to provide a sufficient foundation in chemical bonding, reactions, and some aspects of organic chemistry for students to comprehend essential concepts in modern biology.
- *Interdisciplinary Connections*: With the exception of Earth and Space Science, standards at the Upper Secondary level generally do not highlight fundamental connections between disciplines that would reinforce student understanding of how a concept in one discipline has explanatory power in another.
- *Learning Progressions*: As noted earlier, no individual country's standards were able to serve as an overall exemplar from the Primary through the Upper Secondary levels. A noticeable gap between Lower and Upper Secondary standards in terms of the complexity of content and performance expectations, including the application of mathematics in a number of countries, suggest this is an area that will require close attention as the next-generation U.S. science standards are developed.

[60] Philip M. Sadler and Robert H. Tai, "TRANSITIONS: The Two High-School Pillars Supporting College Science," *Science* 27 July 2007 317: [DOI: 10.1126/science.1144214], 457.
[61] The College Board, SCIENCE College Board Standards for College Success, (The College Board, 2009).

SUMMARY AND CONCLUSION

QUANTITATIVE ANALYSIS: THE SEARCH FOR PATTERNS

Content Expectations

Overall:

An unexpected finding is the priority countries give to physical science in their Primary and Lower Secondary standards, which constitutes 50 percent more than that of Biology in the distribution of the content standards. This finding is notable because physical science is not as heavily emphasized in the United States and suggests that other countries view physical science concepts as central to foundational scientific literacy and as critical to providing a strong base for Upper Secondary courses in Chemistry and Physics.

On average, the countries dedicate the greatest proportion of their Primary and Lower Secondary standards to Biology and Physics content and the least to Earth and Space Science. Again, the attention given to physics is not typical of U.S. standards.

Chemistry:

Properties of Matter and *Energy and Physical/Chemical Change* receive the most attention in Primary, followed by *Solids, Liquids, Gases*. All three categories are maintained at Lower and Upper Secondary but receive less emphasis going up the grades. The implication is that the foundation for the fundamental concepts is laid in Primary and Lower Secondary, permitting instruction to focus on the more complex aspects of the concepts in Upper Secondary and to focus on more advanced topics, such as *Stoichiometry.*

The most emphasized content in Upper Secondary includes: *Organic Chemistry; Chemical Reactions; Properties of Matter; Chemical Bonding and Molecular Structure; Chemical Periodicity; Stoichiometry; and Atomic Structure.* The data reveal that the mathematics of chemistry (*Stoichiometry*) receives a significant amount of attention in Upper Secondary countries' courses, indicating that applying mathematics is key to being successful in postsecondary chemistry courses.

The predominance of Organic Chemistry at Upper Secondary is unexpected. The most attention is given to hydrocarbons, types of organic reactions, functional groups and properties, and the least attention to biochemistry. This finding highlights the lack of a cohesive approach to the chemical underpinnings of modern biology and the resulting need to connect the two disciplines so students understand more and memorize less.

Atomic Structure is a key category in both Chemistry and Physics suggesting that the related topics are considered by countries to be important areas of conceptual understanding in both disciplines. The overlap also represents an area of opportunity in formulating next-generation science standards. Consolidating the treatment of common concepts could avoid duplication of instruction in two U.S. high school courses and encourage in-depth treatment and recognition of the connections among the science fields.

Physics:

The following Physics categories represent the most emphasized content in Upper Secondary and are reasonably supported by related standards in Primary and Lower Secondary: *Motion and Newton's Laws; Electrical Phenomena; Energy and Physical/Chemical Changes; Forces; Wave Phenomena; Atomic Structure;* and *Work, Energy, Power. Motion and Newton's Laws* provides an example of how content builds in complexity from one grade span to the next. The actual content differs, shifting from describing motion, to describing patterns and then to taking up Newton's laws quantitatively at the Upper Secondary level.

Motion and Newton's Laws is an important category in all three grade spans with emphasis on describing motion and forces at the Primary level, describing patterns of motion at the Lower Secondary level, and taking up Newton's laws quantitatively at the Upper Secondary *level.* Of the two categories in modern physics*, Quantum Theory* (5%) receives more attention than *Relativity* (<1%) in Upper Secondary. While both concepts treat complex abstract topics, *Quantum Theory* is more emphasized likely due to its explanatory role in understanding atomic structure.

Electrical Phenomena constitutes a large proportion of standards at all levels (11 percent, 13 percent, and 12 percent at the Primary, Lower Secondary, and Upper Secondary levels respectively), nearly as much emphasis as Newton's laws. Given the dependence of all modern civilizations on the generation and use of electricity, it is perhaps not surprising that educators want all citizens to learn about electrical phenomena as early as possible.

In Upper Secondary Physics, international countries on average also emphasize *Interactions: Science, Technology & Society,* and *Electricity* and to a somewhat lesser extent the *Nature of Science*. This suggests that students in the ten countries are not just expected to learn the content of physics proper, but also the ways that physics is applied in the world around them.

The *Engineering* category is virtually un-represented among the Physics course standards, surprising given the prominence of cross-cutting topics, especially *Interactions: Science, Technology, and Societ*y. (A notable exception is Canada, where the design process has a status equal to that of inquiry.)

Earth and Space Science:

In Earth and Space Science, two of the top three categories remain the same across all grade spans: *Weather & Climate* and *Earth's Features and Materials*. It is also important to note that the three countries that have Earth and Space Science standards at the Upper Secondary level include many standards that relate to Physics concepts.

Only three of the ten countries' standards reviewed provide Upper Secondary school standards for Earth and Space Science standards, indicating that this subject is not as widely recognized as Physics, Chemistry, or Biology as being essential for preparing students to study the sciences at the postsecondary level, similar to the U.S. pattern. Most states include Earth and Space Science in their standards, but in 2007, only three states required an Earth and Space Science course for graduation, and only 11 states offered Earth and Space Science as an elective within science requirements. [62]

Earth and Space Science stands out as the most interdisciplinary of the major disciplines among the Upper Secondary courses in that only 60 percent of the content is discipline-specific with the remaining 40 percent focused on Interdisciplinary or Cross-Cutting content. This is not surprising since Earth and Space Science is an area to which other sciences are applied in an integrated fashion.

Biology:

At the Primary and Lower Secondary level, countries direct significant and sustained attention on average to four categories: *Human Biology and Health & Physiology*; *Interaction and Interdependence in Living Things; Biodiversity;* and *Reproduction, Development and Heredity*. The relatively strong focus on human biology and relationships among living things are topics of importance in scientific literacy from a personal perspective and from a societal perspective on environmental issues. Concern with the latter

[62] American Geological Institute, "The Pulse of Earth Science: An Advocacy Guide, How Education Policy Is Made" <http://www.agiweb.org/education/statusreports/advocacy/ed.html#national> 2010.

category is also evident in the relative emphases placed on two related cross-cutting categories – *Sustainability,* and *Interactions of Science, Technology and Societ*y.

Modern Genetics is not introduced until Lower Secondary and represents a small percentage of the overall standards at that level – an unexpected finding given that Lower Secondary is the demarcation point for scientific literacy and the societal issues surrounding genetic engineering. In Upper Secondary, Modern Genetics rises in prominence ranking fifth among all Biology categories.

The patterns of emphasis in Lower Secondary in Biology and in Chemistry, as previously noted, reveal a lack of attention to critical biochemistry concepts that are necessary for students to understand the bio-molecular content in Upper Secondary Biology. There is a clear need to connect the two disciplines so students understand more and memorize less.

<u>Cross-Cutting Content</u>:

At Primary and Lower Secondary, a full 20 percent of content standards are devoted to Cross-Cutting concepts such as the *Nature of Science*, *Interactions of Science, Technology, & Society*, and *Sustainability*. This is noteworthy in that a significant proportion of the standards in the benchmark countries are dedicated to science, technology, and society and sustainability, indicating countries' concern with the need for students to develop a level of scientific literacy necessary for considering science-related issues impacting one's role as a citizen and as steward of Earth's resources.

At the Upper Secondary level, Cross-Cutting Content comprises about 16 percent for Biology, Chemistry, and Physics, but 11 percent for Earth and Space Science.

<u>Interdisciplinary Content</u>:

Interdisciplinary Content standards (content common to two disciplines) in Biology, Chemistry, or Physics do not represent a significant percentage of course standards, except in Earth and Space Science. It is worth noting that physics-related content comprises more than half of the interdisciplinary standards.

QUALITATIVE ANALYSIS: THE SEARCH FOR EXEMPLARS

Although Achieve's in-depth study of five countries' standards did not yield a single set of standards that could be regarded as wholly exemplary, it did unearth some approaches to structuring and articulating standards that are of interest as we work to develop a new conceptual framework and aligned next generation science standards.

<u>Integrated Science Instruction</u>:

Seven of the selected countries require participation in integrated science instruction through grade 10 (meaning that science content is drawn from the major fields and cross-cutting areas) – and through grade 9 in three countries in the study. This pattern contrasts somewhat with common patterns in the United States where students typically begin to take discipline-specific courses after grade 8 or 9. Students in other countries tend to have one or two more years of interdisciplinary science instruction, likely leading to increased scientific literacy – the basis for the PISA assessment.

<u>Standards Architecture</u>:

Basing standards, either on key concepts in the major fields of life, physical, and earth sciences, or on foundational themes (big ideas) is structurally sound. However, a conceptual framework based on themes common to all of the sciences, as Canada and Singapore do, seems especially powerful for Primary through Lower Secondary grades. Cross-cutting themes provide a matrix for developing a strong story line that can help teachers and students make sense of seemingly disconnected content within and across years of instruction and impart an underlying coherence to the curriculum. Importantly, a theme-based approach provides a filter for selecting among the many core concepts that could potentially be included in a set of standards.

Use of Multiple Examples:

Incorporating multiple examples into content and performance standards, as Canada does, results in multiple benefits. Most importantly, it makes expectations for student performances specific and transparent – the level of rigor is concrete. What is more, examples help learners connect concepts with applications in the real world and help them to explain everyday phenomena. Examples also enhance clarity and accessibility. Incorporating multiple examples, rather than relying on a single example, is important because multiple examples show a range of applications, rather than a single point that can quickly become a limiting factor.

Connecting Standards to Assessment:

Making a meaningful and concrete connection to assessment helps to focus attention on the ultimate goal of raising student achievement. Three countries (Canada, England, and Hong Kong) make a special effort to show how their standards and assessments are aligned. Their approach varies considerably, but all three countries make solid links between the content they expect students to learn and how that learning will be evaluated.

Clarity of Presentation:

Organization and format has an enormous effect on the clarity and accessibility of a country's standards. Canada, Hong Kong, and Singapore have user-friendly standards, and their approaches are similar. England's standards are structured differently but are also accessible.

Engineering Design:

Most of the countries we examined did not give much attention to engineering, even when their standards included "technology" in the title. Thus, Canada's parallel development of inquiry and design stands out. It is carefully thought through and makes fundamental connections between the two processes and also describes a progression of performances for each that explains what increasing proficiency looks like in demonstrating skills in conducting investigations in the natural world and problem solving in the designed world.

Modeling:

Building, applying, and refining models based on evidence is a central pursuit of modern science. Canada provides a comprehensive treatment of modeling, including performances that require students to build, design, and test models in across the grade spans. Standards become more sophisticated in Lower and Upper Secondary, where the use of scientific conceptual models for explaining phenomena or supporting theories is often invoked.

Inclusion:

England and Hong Kong include guidelines for teaching science to all students—an important part of a standards document since guidelines make it clear that science is accessible to the full spectrum of learners.

Progression:

The development of related key concepts across grade spans is generally strong in Primary through Lower Secondary in the five countries' standards included in the qualitative review. However, there seemed to be a gap between the complexity of content and skills (including math applications) in going from Lower to Upper Secondary discipline-specific courses. (The gap was less pronounced in Canada's standards.)

Achieve's detailed analysis also revealed some areas of general weakness that need attention from developers of new standards. These areas include: integration of mathematics applications, emphasis on evidence-based explanations, attention to engineering and technological design and the relationship to modeling, laying foundational knowledge in chemistry for concepts in modern biology, and articulating learning progressions for core concepts from early primary level through discipline-specific courses.

Performance Expectations:

In assessing overall performance expectations (i.e., balance between knowledge expectations and inquiry), an unanticipated finding is that there is a higher proportion of inquiry skills expected of students in Primary (26 percent) than in Lower Secondary (20 percent).

In examining the balance between knowledge expectations and inquiry in Upper Secondary disciplines, Biology and Chemistry courses show the least emphasis on inquiry (with slightly more in Physics) as compared to knowledge expectations, while Earth and Space Science courses require substantially more inquiry skills.

When comparing levels of Cognitive Demand across Primary and Lower Secondary, *knowing* is the predominant level of demand at both levels of schooling. However, in progressing from the Primary to the Lower Secondary, countries begin to place more emphasis on *applying* and *reasoning*.

Not surprisingly, countries place somewhat more emphasis on Advanced Inquiry Skills (i.e., those required for carrying out independent investigations) in both Lower and Upper Secondary grade spans than in Primary.

Upper Secondary courses in Biology, Chemistry and Physics devote less attention to inquiry than do Primary and Lower Secondary levels and also do not show an increase in advanced inquiry skills as compared to Lower Secondary. It is also the case that they place even more emphasis on the least demanding cognitive level, *knowing* than do Primary and Lower Secondary. This pattern highlights the tension that exists between the desire to cover core concepts seen as essential and the need to develop student proficiencies in higher-order thinking skills.

Earth Science is something of an outlier. In Upper Secondary, Earth and Space Science, as compared with the other disciplines, places significantly more emphasis on *reasoning* and on inquiry, including advance inquiry skills.

INTERNATIONAL AND U.S. COMPARISONS IN BIOLOGY

Life Science: International Lower Secondary and U.S. Grades 6-8:

United States' exemplar standards in all three selected sets do not share the emphasis on *Human Biology: Health & Physiology* that the international standards do. This category is absent among the U.S. exemplars. While Massachusetts' students in grades 6-8 are exposed in a general way to the systems of the human body, they learn about these as structures and functions in the context of multicellular organisms. That said, it is important to note that a significant number of states require additional courses in health, in addition to whatever science instruction they require.

Systems, Organs and Tissues: Structure and Functions; Homeostasis, Reproduction, Development & Heredity; and *Cells: Structure & Function* represents more than 50% of the international standards at the Lower Secondary level, matched closely the U.S. at 46 percent.

U.S. exemplars place slightly more emphasis on *Interaction and Interdependence in Living Things* (20%) than do the high-performing countries (16%).

Evolution ranks among the top four categories in the U.S. (14%) while the international standards, place this category at the bottom (3%). The category *Biodiversity* (which is related to Evolution) represents 10 percent of the international standards as compared with an average of more than 14 percent for U.S. exemplar standards.

Modern Genetics is barely introduced in the international standards (3%), while it receives twice the emphasis by the U.S. exemplars (6%). This pattern remains in Upper Secondary where other countries on average show a proportion of 11 percent, versus the U.S proportional emphasis of 20 percent.

Biology: International Upper Secondary and U.S. High School:

For both the U.S. exemplars and the countries in the study, *Cells: Structure & Function*, and *Reproduction, Development & Heredity* rank at the top of the list of Biology categories.

Modern Genetics, along with *Cells: Structure & Function*, and *Reproduction, Development & Heredity* occupy the top three category ranks in the U.S. exemplars – all of which have strong molecular biology components embedded within them, and the lack of basic preparation in related chemistry concepts is a weakness found in both international and United States' biology and chemistry standards. (As is the case in Lower Secondary, *Modern Genetics* in the U.S. exemplars represent almost twice the emphasis of that found in high-performing countries at the high school level.)

CONCLUSION

Achieve undertook this study to inform the development of the NRC conceptual framework and next generation science standards. The findings in this report provide valuable insights into what other countries on average consider to be important content and performances for all students from Primary to Lower Secondary, essential both for foundational scientific literacy and for establishing a base for further study in Upper Secondary science courses. Countries' standards in Upper Secondary provide a window on the content and performances that are seen as important preparation for students to be successful in the major science disciplines—indicating what it means to be STEM-capable—able to meet the demands of a postsecondary course in the same discipline. The report also identifies exemplary features of other countries' standards that are worth emulating, as well as revealing some shortcomings that are also instructive. Much can be learned from a careful consideration of the thoughtful work undertaken by other countries and from outstanding efforts in the U.S., including AAAS *Atlas of Science Literacy*, the NRC *Taking Science to School* and the College Board *Standards of Success* in Science.

The conditions are right for the United States to play a leadership role in forging a new conceptual framework and aligned next-generation science standards, creating a fresh vision for science education and new directions for teaching, learning, and assessment that could contribute significantly to improving student understanding and achievement. Seizing the opportunity to design standards that build on all the work and experience that have pointed the way to the highest student achievement in science internationally has the potential to move the United States into the forefront of science education reform.

About Achieve

Created in 1996 by the nation's governors and corporate leaders, Achieve is an independent, bipartisan, nonprofit education reform organization based in Washington D.C. that helps states raise academic standards and graduation requirements, improve assessments, and strengthen accountability. Achieve is leading the effort to make college and career readiness a national priority so that the transition from high school graduation to postsecondary education and careers is seamless. To make college and career readiness a priority, in 2005 Achieve launched the American Diploma Project Network. Starting with 13 original states, the Network has now grown to include 35 states educating nearly 85 percent of all U.S. public school students. Through the ADP Network, governors, state education officials, postsecondary leaders and business executives work together to improve postsecondary preparation by aligning high school standards, assessments, graduation requirements, and accountability systems with the demands of college and careers. For more information about the work of Achieve, visit *www.achieve.org*.

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