Concept Maps: Making Learning Meaningful
Proc. of Fourth Int. Conference on Concept Mapping
Viña del Mar, Chile, 2010

CONCEPTUAL MAPPING TO FACILITATE REVIEW OF STATE SCIENCE STANDARDS

Jane Heinze-Fry, Museum Institute for Teaching Science, Quincy, Massachusetts, United States

James Gorman, Northbridge High School, Whitinsville, Massachusetts, United States

Jacob Foster, Department of Elementary and Secondary Education, Malden, Massachusetts, United States

Email: jahfry@mits.org, jgorman@nps.org, jfoster@doe.mass.edu

Abstract. The Massachusetts Science and Technology/Engineering Curriculum Framework (MA ESE, 2001/2006) establishes the standards for grades PreK-12. In 2008-2009, the MA Department of Elementary and Secondary Education set out to produce strand maps of the state science standards, modeled on the American Association for the Advancement of Science (AAAS) Atlases for Scientific Literacy (AAAS, 2001, 2007) to facilitate the review and revision of those standards. CmapTools was used for the initial production of these state science strand maps. Strand maps illustrate the progression of science concepts and skills across the PreK-12 span. The strand maps revealed three major features of the current state framework: 1) standards with varying levels of conceptual support across the entire PreK-12 span; 2) recurring patterns of relationships among standards; and 3) varying levels of specificity among standards. In particular, the strand maps revealed standards that were not conceptually supported in early grades, "opportunity-to learn-gaps" in which standards for a topic were at early and late grades but without concepts bridging those years, and some standards that were simply isolated from other standards. Patterns of relationships among standards included diverging and converging concepts and crosslinking within and among topics and strands. Understanding these features is key to revising state standards to enhance progressions of learning across grade spans to make explicit conceptual relationships across grade spans. State standards revised into strand maps offer a foundation to integrate efforts across the educational community that target meaningful learning.

1 Introduction

The first AAAS Project 2061 publication, Science for All Americans (AAAS, 1989), set out to define science literacy and lay out some principles for effective learning and teaching. This was quickly followed by Benchmarks for Science Literacy (AAAS, 1993), specifying how students should progress toward science literacy, recommending what they should know and be able to do by the time they reach grade levels 2, 5, 8, and 12. The Atlases of Science Literacy (AAAS, 2001, 2007) transformed the benchmarks into strand maps that demonstrated how the most important ideas of science fit together and develop across the K-12 grade spans. Each strand map focuses on a topic important for literacy in science, mathematics, and technology and displays the benchmarks across the K-12 span that are most relevant to understanding it. For each benchmark, there is a suggestion of earlier benchmarks upon which it builds and later benchmarks that it supports, thus highlighting the developmental nature of the topic. With these maps as a model, the authors of this paper worked to create strand maps of the current Massachusetts Science and Technology/Engineering standards, to observe patterns revealed by those strand maps, to present standards in a visual format that highlights conceptual relationships, and to suggest how these maps may contribute to the science standards review process and to concept mapping efforts within the broader educational community.

2 The Science Standards Review Process

Massachusetts has been working to incorporate a learning progression perspective in state science standards through the current revision process. Massachusetts' science standards currently put a strong emphasis on content knowledge; the standards are organized around four strands of science at grades PreK-8 (earth and space science, life science, physical science, and technology/engineering) and five "introductory" high school courses (earth and space science, biology, chemistry, physics, and technology/engineering). The first set of Massachusetts' science standards was completed in 1993, with a full revision in 2001, a partial revision in 2006, and now a second full revision underway (expected completion in 2011). (The MA Science and Technology/Engineering Curriculum Framework is available at: http://www.doe.mass.edu/frameworks/current.html). The process for revising state science standards includes assembling a revision panel of volunteer members that are representative of the state's science education community (including practitioners, higher education faculty, and organizational/community membership); identifying and referencing national science standards and assessment documents; drafting and redrafting standards based on research and panelist expertise; and gathering significant public input on those drafts.

The goal of the current review of the state's science standards is to use the revision process to explicitly and systematically draw upon educational research, including available learning progression research (NRC, 2007; Corcorcan et al, 2009), to assure effective support for student learning of key science concepts and skills across time. This paper shows how the development and use of strand maps supports the standards revision by making visible student learning over time and making explicit the connections between topics and disciplines.

3 Strand Maps: Representation of Progressions of Learning

The current Massachusetts science strand maps (available at http://www.doe.mass.edu/omste/maps/) show how students' understanding of ideas and skills that lead to scientific and technological literacy might develop over time from PreK to high school. The Atlas for Science Literacy strand maps (available at http://strandmaps.nsdl.org/) were used as a model for the Commonwealth's strand maps. All Figures in this paper are examples taken from the Massachusetts strand maps. Clear text and color-coding can be viewed via Internet. Each cell of the strand map is an actual state science standard. The arrows between cells represent conceptual (not curricular) relationships between concepts. CmapTools was used to create these maps.

The strand maps enable educators to see how the knowledge and skills students learn in different grades depend on and support one another. Thus, strand maps represent a progression of learning. For example, Figure 1 presents a portion of the Physical Science strand map on force and motion. Foundations of understandings about the motion of objects and their relationship to force are established at the PreK-2 level. Students are expected to 1) demonstrate that the way to change the motion of an object is to apply a force and 2) describe the various ways that objects can move. In Grades 6-8, students are expected to develop ideas of motion further to explain and give examples of how the motion of an object can be described by its position, direction of motion, and speed. (Note there are additional standards on force, not included here). By high school students are expected to construct an even more technical conception of motion and be able to compare and contrast vector and scalar quantities and distinguish between and solve problems involving displacement, distance, velocity, speed and acceleration.

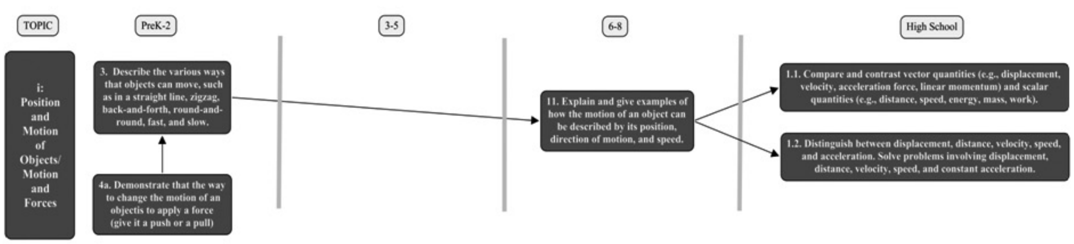

Figure 1. Portion of the Physical Science strand map showing several force and motion standards (From Strand Maps of the 2001/2006 Science and Technology/Engineering Standards http://www.doe.mass.edu/omste/maps/)

As we discuss the strand maps, we will use terminology that is specific to Massachusetts. It is worth taking a moment to define strand, topic, standard, and link. A strand is a science subject or discipline in the state Framework; each strand is represented on its own strand map and assigned a color scheme (Earth and Space Science—blue; Life Science—green; Chemistry—blue-green; Introductory Physics—purple; Technology/ Engineering—yellow-brown). A topic is a major subcategory within a strand and is assigned its own color from within the strand color scheme. For example, there are six topics within the Life Science strand: anatomy and physiology; cells and biochemistry; heredity and genetics; characteristics of living things; evolution and biodiversity; and ecology. A standard is a particular learning expectation. A standard specifies what students should know and be able to do and explicates the knowledge or skills to be assessed.

A link is an arrow that connects standards and represents the conceptual relationship between the two standards. These links are meant to make explicit the concepts that are considered necessary in order to learn later concepts, not any possible connection between concepts. Links within strands are solid; links across or between strands are dashed. An arrow leaving a standard implies that the concept contributes to learning the concept of the next, connected standard. These links are primarily based upon available cognitive research (often limited) specific to a particular idea, general principles of cognitive development (for example, concrete before abstract), logic of the subject matter, and wisdom of practice/ professional judgment.

The development of these strand maps were held to one additional principle: simpler is better. The maps aim for as few arrows and crossings as possible. Placement of topics and concepts on the maps is first by “affiliation to a topic” but when needed standards are moved to place them in closer proximity to conceptually connected standards. Figure 2 presents an excerpt highlighting two topics from the Life Science strand map that illustrate each element discussed here. Topics are listed on the left: characteristics of living things and evolution and biodiversity. Each cell encloses one standard; each arrow represents a conceptual relationship between standards.

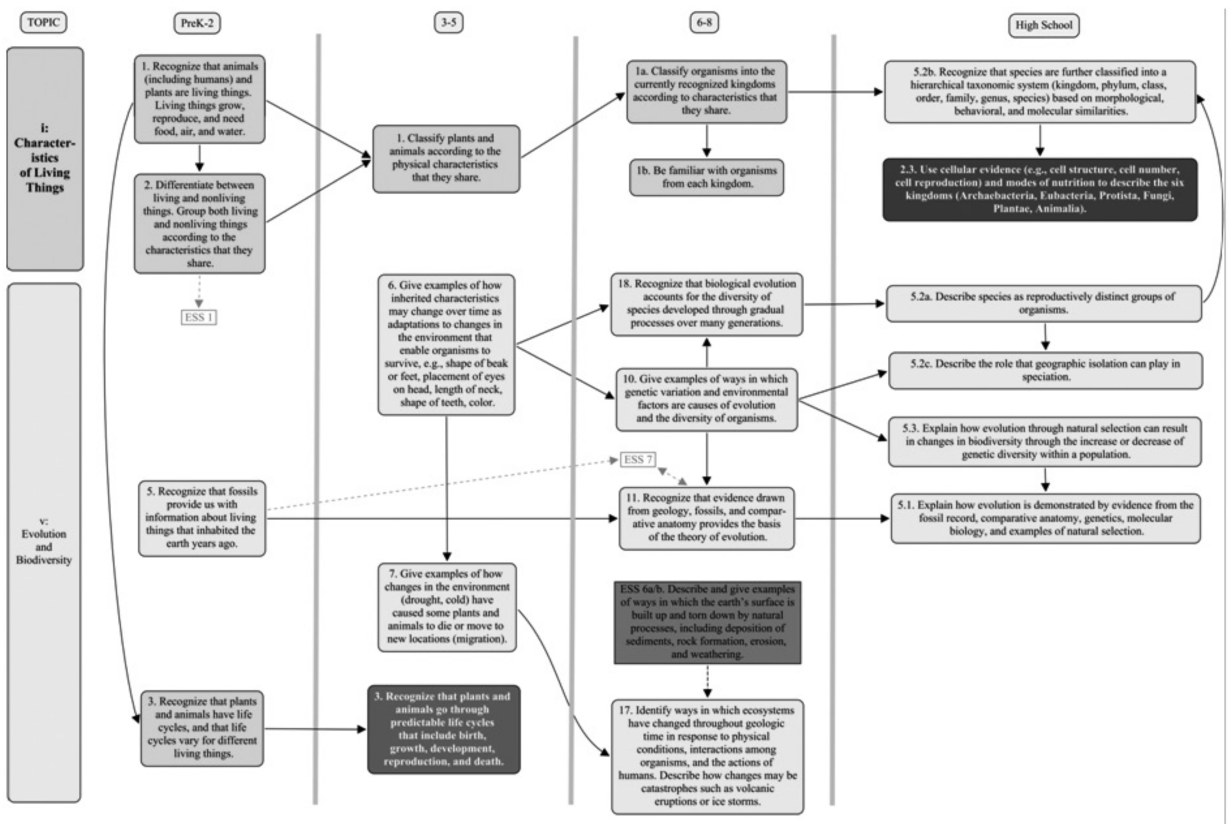

Figure 2. Excerpt from the Life Science strand map showing standards from multiple topics and crosslinking with Earth & Space Science (From Strand Maps of the 2001/2006 Science and Technology/Engineering Standards http://www.doe.mass.edu/omste/maps/).

It is worth taking a moment to distinguish strand maps and concept maps. The structure of a topic can be viewed holistically through both concept maps and strand maps. Content presented in either form provides an opportunity to more easily spot patterns of linkages than content presented through traditional bullet points or numbering schemes. While related, however, strand maps are structurally distinct from concept maps. While strand maps do show conceptual relationships between key concepts, they do not present all possible linkages; they also do not include a variety of linking words that explicate the nature of the relationship between connected concepts; nor are they designed to clarify meaning of particular concepts. Additionally, some standards expressed in strand maps may contain more than one specific concept or skill, depending on how those are written and connected to other standards. This is one distinguishing feature from concept maps, in which a single concept label is generally found within each cell.

4 Features Revealed by Strand Maps

Three general features were revealed by these strand maps: 1) standards that were not conceptually supported at earlier grades; 2) two dominant ways in which standards linked across the grade spans, including diverging and converging concepts; and 3) variations in the specificity of the standards.

4.1 Unsupported standards

Some topics revealed unsupported standards, in which some upper grade-span standards did not have related standards at early grade levels. Sometimes this is quite reasonable given the topic. For example, a number of Chemistry concepts are not reasonably considered by elementary or middle school students. Further, not all grade spans must have concepts for each topic. However, this feature is revealed a number of times in each strand. For example, in engineering design, knowledge and skills needed to successfully represent problems and solutions are missing. In particular, analysis of the AAAS Atlases revealed two concepts fundamental to the development of this topic (Figure 3). Thus, the current framework targeting the topic of Engineering Design might benefit from the addition of foundation standards that emphasize student ability to "draw pictures that portray features of a thing being described" (PreK-2) and to make "scale drawings that show shapes and compare locations of things very different in size." (Grades 3-5).

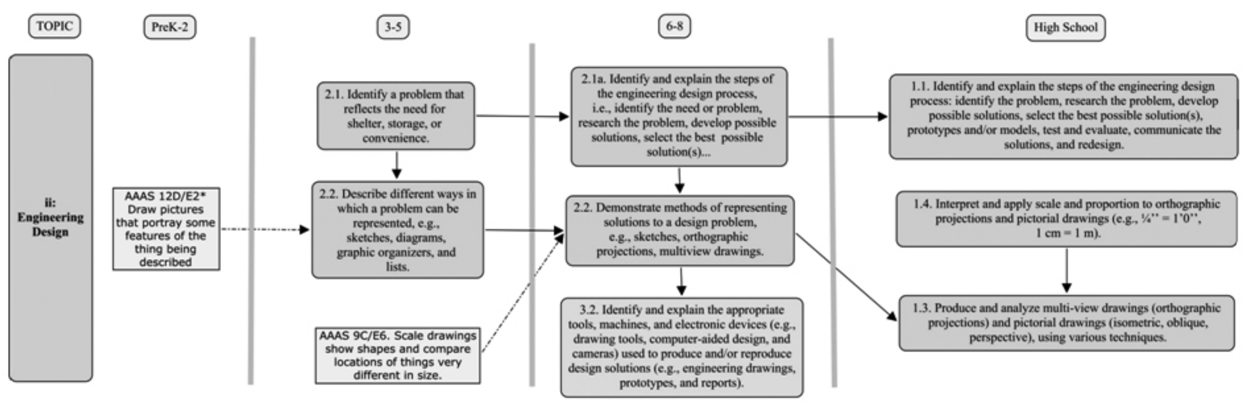

Figure 3. Portion of the Technology/Engineering strand map showing weakly supported standards for representing problems and solutions. Standards from the Atlases of Science Literacy that would better support those begin with "AAAS"(From Strand Maps of the 2001/2006 Science and Technology/Engineering Standards http://www.doe.mass.edu/omste/maps/)

A second type of unsupported standards is represented is an "opportunity-to-learn gap," a break in learning of a topic for a full grade span or more. An example of this is depicted in an excerpt from the Physical Science strand map in Figure 4. The framework stipulates that students begin learning about motion in PreK-2 but then not again until grades 6-8. This presents a large conceptual challenge, as it may be between 4 and 6 years without learning about force and motion. How to address this gap, and others like it, is a key issue in the review process. Likely the reviewers will need to reference national documents such as the AAAS Benchmarks to identify appropriate concepts for grades 3-5.

Figure 4 also illustrates a third type of unsupported standard: isolated concepts. At the PreK-2 level, a standard suggesting that students be able to "recognize that under some conditions, objects can be balanced" is not developed further at any grade level; nor is it conceptually related to any other standard. This is also the case for the high school standard suggesting that students "describe conceptually the forces involved in circular motion." Isolated content sends up a "red flag." Research indicates that arbitrary content is learned in a rote manner; i.e. not learned meaningfully, and is, therefore, less likely to be retained and applied in the future (Ausubel, 1978; Novak, 2009.)

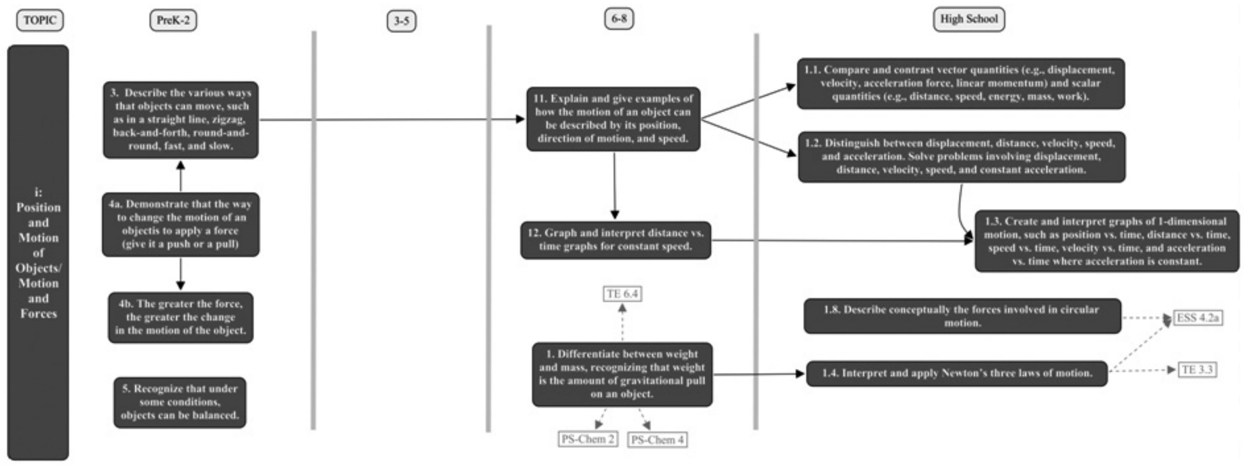

Figure 4. The force and motion topic of the Physical Science strand map showing an opportunity-to-learn gap (grades 3-5) and two isolated concepts (grades PreK-2 and HS). (From Strand Maps of the 2001/2006 Science and Technology/Engineering Standards http://www.doe.mass.edu/omste/maps/)

4.2 Patterns of divergence, convergence, and crosslinking

Three patterns of linkages among standards resonate with Ausubelian Learning Theory: diverging, converging, and crosslinking standards. Awareness of and emphasis on these linkages increase the opportunities for educators to facilitate meaningful learning by PreK-12 students in the classroom.

Diverging standards reflect what Ausubel would have called "progressive differentiation." Subordinate concepts are linked to or 'subsumed' under superordinate concepts. Learners add details to their general understandings, deepening conceptual structure. In Figure 5 below, learning about the general functions of the human body in Grades 6-8 differentiates into six standards at the high school level, each standard targeting a different system and its function.

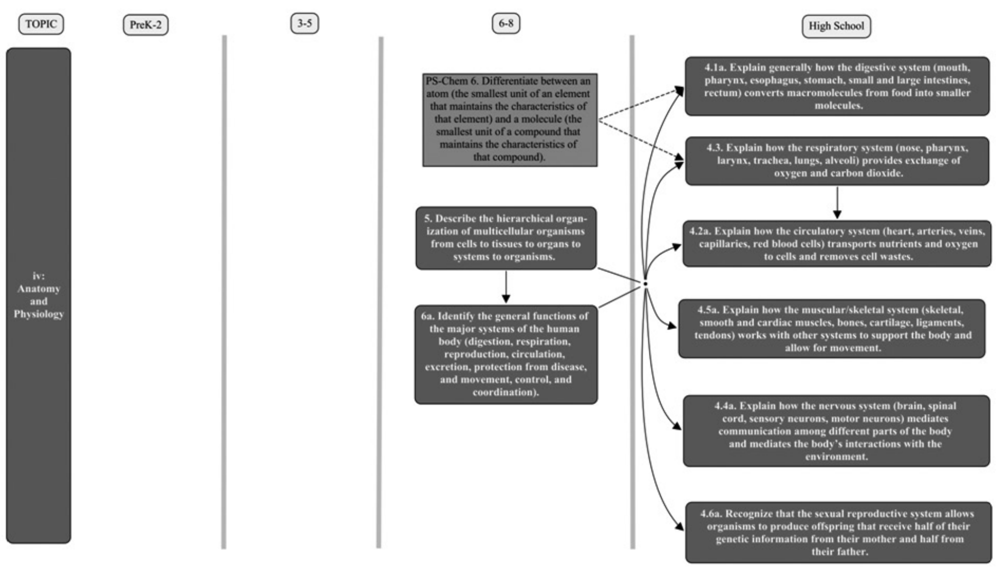

Figure 5. The anatomy and physiology topic of the Life Science strand map showing diverging concepts. This example also shows upper level standards that are unsupported in the PreK-5 grades. (From Strand Maps of the 2001/2006 Science and Technology/Engineering Standards http://www.doe.mass.edu/omste/maps/)

In a second pattern, simple ideas introduced in early years are synthesized into more complex understandings in later years. None of the relevant concepts are more general than the others. The standards represent the learning of many new linkages among concepts that are non-arbitrary and relate to a broad background of generally relevant content in cognitive structure. Ausubel might have labeled the example in Figure 6 as a “combinatorial relationship.” Much construction of knowledge must be carried out in early grades in order for high school students to be able to “provide examples of how the unequal heating of Earth and the Coriolis effect influence global circulation patterns, and show how they impact Massachusetts weather and climate.”

A third pattern, crosslinking between topics within a strand and between strands themselves, is also commonly found throughout the standards. For instance, in Figure 6, the PreK-2 standard “understand that air is a mixture of gases that is all around us and that wind is moving air” is an earth processes and cycles topic standard that lays a foundation for higher-level energy in the earth system topic standards. Additionally, in Figure 6, there are two standards from the Physical Science strand (found in sharp-cornered boxes with dashed arrows) that are crucial to the understanding of a Grade 6-8 standard in this excerpt from the Earth and Space Science strand.

4.3 Inconsistent specificity

Close reading of the standards reveals that some are at considerably different levels of generality. For instance, a relatively large difference in level of specificity is found between two grade 6-8 standards of the “Heredity and Genetics” topic in the Life Science strand. Standard 8 calls for very specific knowledge asking students to “recognize that hereditary information is contained in genes located in the chromosomes of each cell. A human cell contains about 30,000 different genes on 23 different chromosomes.” Standard 9, on the other hand, calls for a more general level of knowledge asking students to “compare sexual reproduction (offspring inherit half of their genes from each parent) with asexual reproduction (offspring is an identical copy of the parent’s cell.)”.

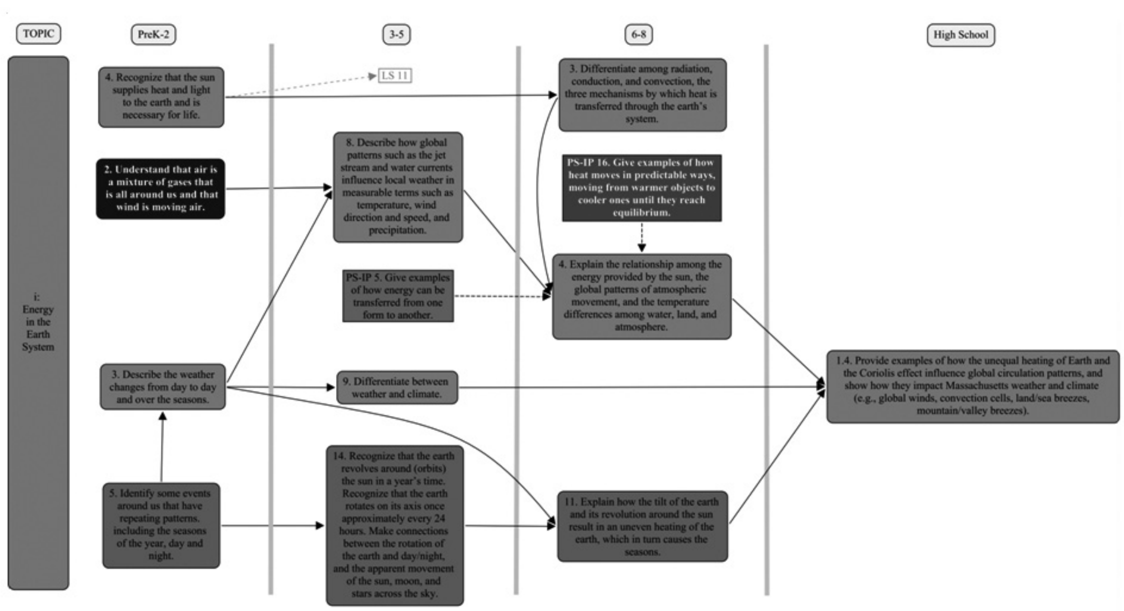

Figure 6. Portion of the Earth and Space Science strand map showing converging concepts leading to the high school standard #1.4. Crosslinking between topics and between standards is demonstrated. (From Strand Maps of the 2001/2006 Science and Technology/Engineering Standards http://www.doe.mass.edu/omste/maps/)

5 Using Strand Maps and Learning Progression Research to Revise State Standards

Learning progressions can account for how students think and learn about science from a cognitive perspective. A learning progression, by definition, bridges the scientific version of a big idea to the intuitive ideas children develop about it before formal instruction (Corcorcan et al, 2009; Wiser & Smith, 2009). While learning progressions are research-based, they are hypothetical; they are ideal paths for successful conceptual development about a big idea; they propose how a network of knowledge about a big idea could coherently evolve over long period of time from young children's ideas if students are exposed to curricula with appropriate consideration given to "concepts, stepping stones, levers, and linchpins." (Wiser & Smith, 2009; Wiser et al, 2009). That is why a learning progression can be so useful; it invites standards developers to design standards that will bring the learning progression about according to cognitively appropriate core ideas.

Considering student cognition from a learning progression basis allows standards and curriculum developers to account for prior beliefs and transitional ideas, even if those ideas are not scientifically accurate. "How students get there" is about their cognitive reconceptualization which can be seen in learning progressions that promote more of a holistic view of student thinking about scientific ideas. Finally, a learning progression approach requires careful consideration of how science content knowledge and inquiry skills relate, because how students cognitively engage with science content is key to their learning.

While we see the great value and potential of learning progressions on standards development, it is important to note that a full standards development process based on learning progressions is not possible at this time due to the early state of learning progression research. As such, the best we can do at this time is to revise our current standards to include what cognitive insights are now available. Using strand maps to visualize the progressions of standards is key to this process. For the present, our revision process will use what research is available, as well as collective wisdom of those teaching students, to appropriately address the features or patterns identified in the strand maps that may hinder student learning of science. Strand maps will help us enhance the relationships and progressions of standards to better support student learning of science.

6 Possible Extensions and Next Steps

Strand maps take a big step toward showing the Pre-K-12 grades connectivity among the Massachusetts standards. Standards connected to prior standards imply that curriculum, teacher's instruction, and student's learning will be targeted toward connectivity. Such an approach foregrounds meaningful learning over rote learning.

Strand maps offer an opportunity for an educational learning community to engage in ways that promote meaningful learning in students. By using CmapTools to visualize and manipulate the strand maps, curriculum coordinators and teachers can easily link their work to the standards, thus allowing them to visually demonstrate how their curriculum aligns with the commonwealth's curriculum frameworks. This process is considerably easier than past efforts to visualize such alignment (Heinze-Fry, 2006).

Both strand mapping and concept mapping are tools that facilitate meaningful learning within the educational community. Both target connected knowing of concepts rather than arbitrary rote learning and isolated content. They differ, however, somewhat in target audience and scale. Strand maps, such as those demonstrated by the National Science Digital Library AAAS maps, are hypothetical conceptual superhighways linking the big ideas of science and demonstrating possible linkages among them. Such maps are especially useful to standards-setting State Departments of Education and Curriculum Coordinators for individual school systems. Concept maps, on the other hand, are more often created by teachers to demonstrate how they are connecting concepts within their discipline. Students create concept maps to demonstrate how they are connecting new concepts to their prior knowledge and particular exemplars that clarify the meaning of that concept for them. Novak describes how students, using skeletal expert concept maps, can create their own differentiated learning using Internet resources, experiments and field experiences, and other learning experiences (Novak, 2009). Over time, these maps can demonstrate lifelong learning over the preK-adult span. Portfolios demonstrate such an approach.

CmapTools is software which can be used to link all of these efforts together. Curriculum coordinators can parse the requisite knowledge into expert concept maps that clearly label the relationship between concepts. The advantage here is that the curriculum coordinator can directly link their school or school system's goals to the standards while fleshing their meaning out for educators. Teachers can also link their instructional efforts to the curriculum coordinators work. Students, in turn, can demonstrate mastery of subject matter by linking their learning efforts to the teachers' instruction. A demonstration of this vision can be found at http://cmapspublic3.ihmc.us/rid=1HL3HCVNB-8H9KH3-J6J/Vision.cmap. The vision demonstrates that the educational professional and governing institutions can articulate the standards of scientifically literate citizens, and school systems, individual teachers, and students can demonstrate their unique pathways to addressing those standards.

7 Summary

Using the Atlases of Science Literacy as a model, strand maps of the Massachusetts Science and Technology/Engineering Framework were created to facilitate the curriculum review process. Through visual representation, these maps demonstrate unsupported standards, patterns of divergence, convergence, and crosslinking, and standards of inconsistent specificity. Using these strand maps and research in cognitive science and learning theory, revised maps are likely to show more complete learning progressions in the preK-12 grade spans. Highlighting the converging, diverging, and crosslinking standards as well as the use of CmapTools in creating the standards opens opportunities for further integration of all members of the educational community.

References

American Association for the Advancement of Science (AAAS). (1989). Science for All Americans. Oxford University Press: New York, New York.

American Association for the Advancement of Science (AAAS). (1993). Benchmarks for Science Literacy. Oxford University Press: New York.

American Association for the Advancement of Science (AAAS). (2001). Atlas of Science Literacy, Volume 1. American Association for the Advancement of Science and the National Science Teachers Association: Washington, DC.

American Association for the Advancement of Science (AAAS). (2007). Atlas of Science Literacy, Volume 2 American Association for the Advancement of Science and the National Science Teachers Association: Washington, DC.

Ausubel, D. P., Novak, J. D., and Hanesian, H. (1978). Educational Psychology: A Cognitive View, Second Edition. Holt, Rinehart, and Winston, Inc.: New York, New York.

Corcoran, T., Mosher, F., and Rogat, A. (2009). Learning Progression in Science: An evidence-based approach to reform. Consortium for Policy Research in Education: Philadelphia, Pa.

Heinze-Fry, J. (2006). CmapTools Facilitates Alignment of Local Curriculum with State Standards: A Case Study. In Concept Maps: Theory, Methodology, and Technology: Proceedings of the Second International Conference on Concept Mapping. Cañas, A. J. and Novak, J. D. eds. San Juan, Costa Rica.

Massachusetts Department of Elementary and Secondary Education (ESE). (2001/2006) Massachusetts Science and Technology/Engineering Curriculum Framework. Malden, Massachusetts, USA.

National Research Council (NRC). (2007). Taking science to school: Learning and teaching science in grades K-8. Committee on Science Learning, Kindergarten through Eighth Grade. Duschl, R.A, Schweingruber, H.A., and Shouse, A.W. editors. Board on Science Education, Center for Education, Division of Behavioral and Social Sciences and Education. The National Academies Press: Washington, DC.

Novak, J. D and Cañas, A. J. (2008). The Theory Underlying Concept Maps and How to Construct Them. Technical Report IHMC CmapTools 2006-01 Rev 01-2008 available at http://cmap.ihmc.us/publications/researchpapers/theorycmaps/theoryunderlyingconceptmaps.htm

Novak, J. D. (2009). Learning, Creating, and Using Knowledge: Concept Maps as Facilitative Tools in Schools and Corporations, Second Edition. Routledge Taylor & Francis Group: New York, New York.

Novak, J. D. (2004). Reflections on a Half-Century of Thinking in Science Education and Research: Implications from a Twelve-Year Longitudinal Study of Children's Learning. Canadian Journal of Science, Mathematics and Technology Education. Volume 4: Issue 1, pp. 23-41. Routledge Taylor & Francis Group: New York, New York.

Wiser, M., and Smith, C. (2009). How does cognitive development inform the choice of core ideas in the physical sciences? Commissioned paper for National Research Council: Committee on Core Ideas in Science: Washington, DC.

Wiser, M., Smith, C. L.,Doubler, S., and Asbell-Clarke., J. (June 2009). Learning Progressions as a Tool for Curriculum Development: Lessons from the Inquiry Project. Paper presented at the Learning Progressions in Science (LeaPS) Conference. Iowa City, Iowa.