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Towards Coherence in Science Instruction: A Framework for Science Literacy

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One of the most powerful ideas underlying science is that a small number of simple laws guide the behavior of the natural world. If this is true, why is science not taught that way in our schools? Why are we not told the laws and then shown how these apply in different situations to gain understanding and insight into natural systems? Instead, at least at the K-12 level, science is often taught as a list of facts and definitions to be memorized. However, it is the underlying laws that tie them together, providing coherent insights, and allowing us to make transformative intellectual leaps resulting in new understandings, discoveries and technologies.

A functional knowledge of the laws, and an ability to apply them in different situations, defines scientific literacy much more than any particular list of memorized scientific facts. Yet, vocabulary, definitions, and facts are important, but real understanding of science comes when students can apply their learning to a variety of new and

different situations. If K-12 educators were to focus more on the fundamental laws and concepts undergirding science, then our students could gain a deeper and more flexible understanding of science. A transformation to this way of teaching may begin to address the often-noted crisis in U.S. science achievement.

By whatever metric one consults – whether the international benchmarks from the Third International Mathematics and Science Study (TIMSS) or the Program for International Student Assessment (PISA) or the nation's report card of the National Assessment of Educational Progress (NAEP) – the portrait of U.S. science achievement is consistently mediocre – a portrait virtually unchanged over the past 20 years. Although the science performance of U.S. students is typically relatively slightly better than their mathematics performance, it remains uninspiring at best.

The most recent science scores from the NAEP provide a sobering example. Fewer than half of U.S. fourth, eighth and twelfth grade students were deemed proficient in science. Even more disconcerting was the fact that very few students – no more than one or two percent in any of the three grades – performed at the advanced level (NCES, 2011).

One hypothesis explaining this lackluster achievement pattern is that the U.S. has a fragmented curriculum (Schmidt, McKnight, Raizen, 1997). Analyses of curriculum materials from around the world (1995 TIMSS) provided the basis for this inference finding that the U.S. science curricula had a splintered vision, one that lacked the coherence, rigor, and focus characterizing those in higher achieving countries (Schmidt, Wang, McKnight, 2005).

WHAT IS COHERENCE?

Empirically inspired by the curricula from the top-achieving 1995 TIMSS countries and drawing upon Bruner's cognitive psychology, the concept of curricular coherence was developed as follows (Schmidt, Wang, McKnight, 2005, page 528):

... If one of the major purposes of schooling is to help students develop an understanding of the various subject-matters deemed important by a society, such as mathematics and science, then the definition of 'understanding' is important to examine as a way of viewing each discipline intended for schooling...

Bruner (1995:333) suggests that:

...to understand something well is to sense wherein it is simple, wherein it is an instance of a simpler, general case. ...In the main, however, to understand something is to sense the simpler structure that underlies a range of instances, and this is notably true in mathematics.

Bruner's definition implies that the logic of the content in a discipline is important and that, for example, the goal of helping students understand ... is facilitated by making visible to them an emerging and progressive sense of its inherent structure. Bruner describes this as:

...opt[ing] for depth and continuity in our teaching rather than coverage ... to give ... [the student] the experience of going from a primitive and weak grasp of some subject to a stage in which he has a more refined and powerful grasp of it (p. 334)

We define content standards, in the aggregate, to be coherent if they are articulated over time as a sequence of topics and performances consistent with the logical and, if appropriate, hierarchical nature of the disciplinary content from which the subject-matter derives. This is not to suggest the existence of a single coherent sequence, only that such a sequence reflect the inherent structure of the discipline. This implies that, for a set of content standards 'to be coherent', they must evolve from particulars ... to deeper structures. It is these deeper structures by which the particulars are connected ... This evolution should occur both over time within a particular grade level and as the student progresses across grades.

However, rather than a coherent sequence of carefully selected topics either within or across grades, U.S. science curricula often have appeared to be little more than a "to-do" list of topics to be covered in the classroom. This was especially the case in

science given that K-8 science is derived from multiple disciplines rather than a single discipline.

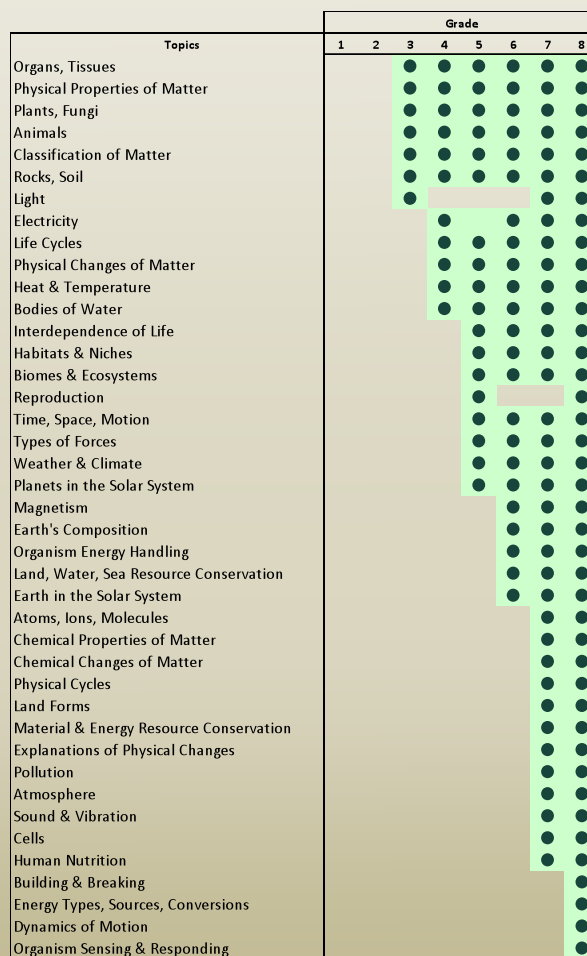
PATHS TOWARD CURRICULAR COHERENCE

How can the U.S. achieve a more coherent school science curriculum? A measure of coherence in the U.S. K-12 mathematics curriculum, as seen in the recently developed Common Core State Standards for Mathematics, was possible by using international data as well as paying attention to the logical hierarchical internal structure of the mathematics discipline (Common Core State Standards Initiative, 2010). However, unlike mathematics, science is not a single discipline but a collection of interrelated disciplines, each with its own structure that includes many connections to the other sciences.

As a result, the science curriculum in K-8 schooling (especially in grades 6–8) typically covers the separate disciplines in different grades. Although national standards followed by all states are not currently in place, careful sets of science content standards to guide standards-based reform have been developed (AAAS, 1989; National

Research Council, 1996, 2011). The National Science Foundation has funded the development of exemplary science curricular materials based on these standards — materials suitable for immediate implementation in U.S. classrooms. Yet these current standards suffer from a lack of focus, with topics partitioned into disciplinary silos that make coherence difficult to achieve. The main underlying story of science, the laws that describe the natural world and define its

Figure 1: A+ COUNTRIES' CURRICULAR COHERENCE MODEL IN SCHOOL SCIENCE



coherence, are lost in the details stacked within the silos. Is the solution the design of new standards or a different way of approaching the whole issue?

International Benchmarking

The first approach is to examine the standards from some of the highest achieving countries and, informed by them, to revise our standards (Schmidt, McKnight, Raizen, 1997). This effort began as a simple empirical analysis to see what commonality might be found in the set of curriculum standards that were in place and governed classroom instruction in those countries that statistically outperformed most other countries that participated in the 1995 TIMSS, referred to here as the A+ countries. What emerged from this analysis in mathematics was an exemplar of a relatively small number of topics focused upon in each grade and sequenced across the years of schooling in a manner that reflected the internal logic and coherence of the discipline.

With science, a different kind of pattern emerged – one that cut across the four science disciplines that are the focus of school science, i.e., biology, chemistry, earth science and physics. This pattern, illustrated in Figure 1, introduced topics at each grade and often retained them in later grades once introduced, but across the grade levels, the coverage of the topics became increasingly more complex.

Supporting this general pattern were themes at each of several grade bands.

... [M]ost of the science topics introduced in the primary grades (grades 3 and 4) continue in the curriculum through grade 8. These topics appear to serve the same role as the ‘buttresses’ did in mathematics. They represent some of the most fundamental concepts of science: (1) the classification of living organisms and their systems—plants, fungi, animals, organs, tissues, and life-cycles; (2) the classification of the earth’s physical features—rocks, soil, and bodies of water; (3) the classification of matter as well as physical properties and changes of matter; and (4) different forms of energy—light, electricity, and heat. These fundamental topics come from physics, biology, and earth science, and run through the first 8 years of schooling (although for three of the A+ countries this coverage is not intended to begin until the 3rd grade).

All of these are broad topics for which the intended coverage could deepen from year-to-year... There are similar instances in science of deepening the coverage of a topic by additional theoretically-linked topics, but there is also considerable deepening of coverage that can occur within a single topic, probably more so than in mathematics. However, it is clear for these 12 basic topics that they are deemed important and fundamental enough among the top-achieving countries to be included at the start of the science curriculum and to continue in some fashion through grade 8.

The lower middle grades (grades 5 and 6) continue these same topics (with the exception of light and electricity), but introduce additional and more complex topics. Thus, the biology concepts presented in the primary grades dealing with the classification of living organisms

and their morphology provide a foundation for the study of (1) within-organism development and (2) the interaction of living organisms both with other organisms and with their environment. These latter topics mainly deal with ecology and environmental science. Within-organism development focuses on the basic aspects of life-cycles themselves and on reproduction.

Some topics in earth science are also related to concurrent life-science topics for the lower middle grades. While students are expected to learn how living organisms interact with their environment, the supportive topics from earth science for these grades are weather and climate and the composition of the earth. The solar system is the other major thrust of the earth-science curriculum in grades 5 and 6. In the physical sciences, building on the study of matter and energy begun in grades 3 and 4, the top-achieving countries intend their students to study magnetism, types of forces (such as gravity), and ‘time, space and motion’ at grades 5 and 6. The latter two topics are conceptually related to the solar system topic included in these lower middle grades.

In the upper middle grades (i.e. grades 7 and 8), the science curriculum of the top-achieving countries intends students to study chemistry and related topics for the first time. This includes atoms, ions, and molecules; explanations for physical changes (including boiling, freezing, and dissolving); chemical changes such as oxidation-reduction, and explanations for such chemical changes (e.g. covalent bonding and electron configurations). Physics topics are also included—sound and vibration types and sources of energy such as potential and kinetic; and the dynamics of motion. ‘Light’ also returns as a topic, having been introduced in grade 3 although absent after that.

The earth science topics introduced in grades 7 and 8 build on the concomitant physics and chemistry topics introduced in those upper-middle grades. These include physical cycles such as the rock-and water-cycles; plate tectonics; the atmosphere; and conservation topics such as pollution. In the life sciences, using newly introduced physics and chemistry topics and building on the study of organs and tissues, the A+ countries introduce biochemistry and the physiology of organisms—covering such topics as sensing and responding, cells (including cell membranes, mitochondria, and vacuoles), and human nutrition.

In one sense, the science curriculum is similar to mathematics in having an upper triangular structure with three tiers. However, science’s first tier serves as the unifying element (the curricular ‘buttress’), since those fundamental topics introduced in grades 3 or 4 continue throughout the rest of the first 8 years of schooling. The lower-middle grades (i.e. grades 5 and 6) serve as the second tier and focus mainly on ecology and environmental science (supported with topics from both biology and earth science), the solar system (supported by physics topics), and magnetism. The upper middle grades (i.e. grades 7 and 8) provide the third tier as they did for mathematics; in the top-achieving countries they are focused on chemistry, physics, biochemistry, physiology, and earth science topics that build on chemistry. (Schmidt, Wang, McKnight, 2005, pages 544-547)

This pattern was in contrast to an amalgam of the then existing state standards. This analysis led to the conclusion that, in comparison, U.S. science standards included far more topics at every grade level and often included complex advanced

topics before the underlying basics had been covered. Consequently, much of the science in U.S. schools emphasized complex science vocabulary, scientific classifications, and taxonomies rather than focusing on any set of scientific laws or principles or a few key underlying concepts that would provide a deeper understanding together with real empirical inquiry. Perhaps the consequence is best expressed by a California science teacher who said, “I have so many state standards I have to teach... it takes time away from what I find most valuable, which is to have them inquire about the world” (Harmon, 2011).

An illustration of the difference in focus and emphasis between the standards of the highest achieving countries and those in the U.S. is evidenced in the area of human biology in the middle school science curriculum. The U.S. focuses on identifying the names and functions for parts of the eye whereas the focus in the higher achieving countries is on the chemical processes by which the information carried by photons entering the eye is perceived, transmitted to the brain, and interpreted into a visual image. Another comes from earth science. In the U.S. the water cycle appears in a broadly descriptive manner as a physical process years before students encounter the basic chemistry upon which an understanding of this process depends. In the higher achieving countries, the sequence is reversed.

These two examples illustrate how the A+ countries have coherence reflected in their standards yet still suffer from too many topics in a year (see Figure 1). This approach with the sciences yields only a measure of coherence at the micro level, the sequencing of topics, without establishing a focused, coherent sense of science literacy, a sense of the larger picture, of how all science topics adhere in a related whole. Thus topics are still mostly separated and inter- and intra-disciplinary connections are not made explicit or obvious. They simply provide various extensive “laundry lists” of far too many topics.

Although employing this empirical A+ approach yields increased coherence for the science curriculum, it still suffers to some extent from the silo effect and also includes far too many topics, especially in the middle grades. It also seems that the deeper themes of science that cut across the various disciplines – an understanding of the fundamental concepts, the core of scientific literacy – may be discernable but aren’t explicit. Mindful of this, we decided to look at the issue of coherence with a different set of lenses. We began by asking the question of what constitutes scientific literacy, the fundamental concepts that a society would want citizens to grasp in order to understand new science developments and their social implications.

A Different Approach

The National Science Foundation supported an effort to articulate a set of fundamental science concepts for organizing and providing coherence to K-8 science instruction as a part of the Promoting Rigorous Outcomes in Mathematics/Science Education (PROM/SE) project. To do this, a group of nationally recognized research scientists and science educators were brought together. This group sought to identify and articulate broad concepts that transcend disciplinary structures. In addition, the group sought to identify specific ideas that are considered fundamental to the learning and understanding of science for the twenty-first century.¹

The idea informing this approach was that a small number of key concepts that govern the natural world that transcend or cut across the various science disciplines might serve to limit the number of essential topics. Other topics in standards might be subordinated to ones that play more important roles according to these key concepts. Consequently, this reduced set of topics might more easily be woven into a coherent unfolding of key science concepts and principles through the science “stories” in which they are embedded – “stories” that are

intrinsically interesting to students and that provide the needed basis for understanding science.

The result of this process is a set of principles or concepts the group informally titled the “8+1” (See Figure 2). These are conceived as responding to the overarching question, “How do we know what we know?” the answer to this question is through inquiry, which is the “+1” in the “8+1”. Responding to two further questions about the natural world: “Of what are things made?” And, “How do systems interact and change?” yield the 8 fundamental concepts of science. Thus the

Figure 2: The “8+1” Fundamental Science Concepts

Preamble: What is science? What is science for?

- *Science is able to explain the way the natural world works by means of a small number of laws of nature.*
- *These laws, often expressed mathematically, are explored using tools such as observation, measurement, and description.*
- *Information is synthesized into understanding through creative thought with predictions continuously tested by observation and measurement.*

How do we know what we know?

Inquiry (+1)

Of what are things made?

1. Everything is made of atoms and atoms are composed of subatomic particles.
2. Cells are the basic units of organisms.
3. Electromagnetic radiation pervades our world.

How do systems interact and change?

4. Evolution: Systems evolve and change with time according to simple underlying rules or laws.
5. Parts of a system move and interact with each other through forces.
6. Parts of a system can exchange energy and matter when they interact.
7. Physical concepts like energy and mass can be stored and transformed, but are never created or destroyed.
8. Life systems evolve through variation.

distinguishing feature of science as inquiry is viewed as the means by which one not only responds to the overarching question but how one can formulate responses to the other two. Three concepts are viewed as responses to the question, “Of what are things made?” and the last five concepts are viewed as responses to the question about how systems interact and change.

These concepts have evolved from the scientific enterprise that seeks to understand the natural world. Although the “8+1” concepts appear to be fairly simple and straightforward, they are very powerful for achieving deep understanding when applied to specific science topics and phenomena. The science working group continues to discover deeper levels of understanding for themselves as the concepts are applied to increasingly complex science topics. Science is able to explain the way the natural world works by means of a small number of natural laws. These laws are often expressed mathematically and are explored empirically using tools such as observation, measurement, and description. Information is then synthesized into an understanding through creative thought with predictions continuously tested by observation and measurement.

The “8+1” are not to be viewed as a competing set of standards but rather as a set of fundamental concepts that support and provide connection among the many different topics typically included in science

standards. The goal in creating the “8+1” is to support whatever standards are the focus of classroom instruction as well as whatever textbooks or materials are in use; to go beyond the facts and to connect them to the “8+1” fundamental concepts.²

The basic idea behind the “8+1” is that the units or topics specified in standards are to be viewed as the particulars, important in and of themselves, that can also be used to provide a deeper understanding that goes beyond the specifics to the simpler structure that underlies the particulars. This is what Bruner, from a cognitive science viewpoint, defines as understanding; “to understand something well is to sense... wherein it is an instance of a simpler general case.” This sense of understanding is central to our conception of scientific literacy. Drawing upon Bruner’s sense of the word, science literacy is defined by *understanding* science rather than possessing an encyclopedic mastery of some canonical list of science facts or vocabulary.

The beauty of this approach towards creating coherence in science instruction is that it supports the intended science curriculum even in the absence of a “common core” set of standards, such as with mathematics, because it goes beyond the particulars of any set of specific topics as found in state standards. In this sense the “8+1” serve as the foundation that supports and informs instruction and the effort to help students make sense of the

natural world. Coherence then lies not only in the sequencing of topics, which is more the model of coherence seen in the mathematics Common Core State Standards, but also, and more importantly, in the many connections that can be made explicit among the topics through the “8+1”. These fundamental concepts are always relevant; some, if not most of them, always undergirding whatever topic may be taught.

However, this is not to say that coherence as seen in the standards of the highest achieving countries, in the sense of appropriately sequencing topics, is unimportant or should be ignored. Recognizing the appropriate sequencing (National Research Council, 2007; Michaels, Shouse, Schweingruber, 2008) of topics, taking into account the logic of the disciplines involved would only add another layer to the desired coherence. Also given the multidisciplinary nature of science, the interconnections among topics become a key to achieving coherence and need to be made explicit. Both types of emergent coherence are vitally important in making sense of the natural world, in coming to understand science rather than simply regurgitating scientific facts, vocabulary, and definitions. Simply put, not all standards provide an equal basis from which to apply the “8+1”. The same is true of the many textbooks and kits supporting science instruction.

These two approaches to achieve coherence work together: some topics are conceptually basic to understanding others yet the fundamental concepts can be fruitfully employed to connect topics within and across grades and within and across the various science disciplines in a manner that promotes an understanding of science and the scientific perspective on the natural world. Genuine science literacy develops from seeing the 8+1 concepts as tools to be used in making sense of the world, particularly as one encounters new or novel information/phenomena in the natural world.

IMPLEMENTING THE “8+1”

We began the implementation process by first mapping the eight concepts against various state standards, the National Research Council’s National Academy of Science standards, and the American Association for the Advancement of Science (AAAS) benchmarks to ensure that they were comprehensive and would adequately provide the conceptual foundation and necessary principles for understanding all the topics included in these standards. Since these standards represented the current thinking (and still do until the new standards become available) of what should be covered, this sort of adequacy becomes a type of content validity assessing whether the “8+1” can be applied to the full range of typical K-12 science topics.

The science working group not only examined whether this set of concepts

could be used to explain the topics (actually the scientific phenomena represented by the topics) in the current standards but also practiced applying them to various instructional units and lessons found in current textbooks and resource materials in the participating PROM/SE districts. One such lesson illustrates how the “8+1” provides a conceptual framework to support instruction and to help the students (in Bruner’s terms) sense this topic as one more instance of the simpler structure that underlies science. This process is illustrated in Figure 3.

The technology of paper, a sixth grade lesson, at first appeared an unlikely lesson to connect to many of the 8+1 concepts. However, as the group reflected on the lesson many connections became apparent. For example, paper is made from the fibrous parts of plants such as woody tree trunks. These fibrous parts are composed of cellulose, a compound made up of multiple sugar molecules that are composed of carbon, hydrogen and oxygen atoms (concept 1). Plant cells make the raw materials from which paper is made (concept 2). Plants use the energy from the sun, carbon dioxide from the air, and water to photosynthesize sugars. Sugars are the raw materials from which bark and wood are made. Wood fibers are very long chains of sugars linked together (concept 3). After the bark is removed from tree trunks, the wood that remains is chipped into smaller pieces, mixed with water, and heated in a pressure cooker-type device. After heating,

the mixture is washed leaving only the long cellulose fibers (concept 4). Bark is removed from tree trunks by rolling the trunks together. As the trunks rub together the bark is loosened and separates from the wood. Chippers are made of steel blades. The force of the steel blades against the wood separates the pieces of wood into small chips (concept 5). Plants use the energy from sunlight to form energy rich substances (sugars) that in turn are made into other substances such as wood. Animals eat sugars for the energy they provide. When wood burns the energy stored in it is converted into heat and light (concept 6). The mass of wood at the start of the paper making process is equal to the mass of the wood fibers produced by the process of chipping and steaming plus the mass of the water and the substance that holds the wood fibers together in the untreated wood (concept 7). In nature, a wide variety of plants exist from which paper can be made. Examples include Chinese cabbage, celery, broccoli, turnip, and dandelions (concept 8). Finally, using an inquiry process, students could grow a variety of plants from seeds, harvest them, make paper and compare the qualities of the various papers.

**PROFESSIONAL DEVELOPMENT:
CONCEPTUALLY GROUNDED AND
CONTENT RICH**

How can the concept of curricular coherence be leveraged to improve students’ science learning in schools? This was one of the undergirding questions

Figure 3: Connecting Fundamental Science Concepts to a Sixth Grade Instructional Unit³

		The Technology of Paper
Fundamental Concepts of Science	1. Everything is made of atoms.	Paper is made from fibrous parts of plants such as woody tree trunks, grassy stems & leaves, and cottony seeds. Plant fibers consist of the compound cellulose that is made up of sugar molecules, which are composed of carbon, hydrogen, and oxygen atoms.
	2. An organism consists of cell(s).	Plant cells make the raw materials from which paper is made. Bark and wood are synthesized in the cells of trees (plants).
	3. Electromagnetic Radiation	Plants use energy from sunlight, carbon dioxide from the air, and water to make sugars; a process called photosynthesis. These sugars are the raw materials from which plants make other substances such as bark and wood. Wood fibers are very long chains of linked sugars.
	4. Systems Change	After removing the bark, the rest of the wood is chipped, mixed with water, and heated in a type of pressure cooker. After heating, the mixture is washed leaving only the long fibers of cellulose.
	5. Forces	Bark is removed from tree trunks by rolling the trunks together. As the trunks rub together the bark is loosened and separated from the wood. Chippers are made of steel blades. The force of the steel blades against the wood separates the pieces of wood into small chips.
	6. Exchange of Matter and Energy	Plants use the energy from sunlight to form energy rich substances (sugars), which in turn are made into other substances such as wood. Animals eat sugars for the energy they provide. When wood burns the energy stored in it is converted into heat and light.
	7. Energy/ Mass Conservation	The mass of wood at the start of the paper making process is equal to the mass of the wood fibers produced by the process of chipping and steaming plus the mass of the water and the substance that holds the wood fibers together in the untreated wood.
	8. Life systems vary	The natural world has a wide variety of plants from which paper can be made; e.g., Chinese cabbage, celery, broccoli, turnip, dandelions, etc.
	(+1) Inquiry	Students will grow plants from seeds, harvest and make paper. Plants will be grown under varying fertilizer conditions. Growth will be tracked and the quality of the paper produced will be compared.

informing all PROM/SE activities and especially the professional development efforts with teachers and district curriculum leaders such as curriculum coordinators, principals, and superintendents. Some research appears to affirm that content rich professional development for teachers is most likely to lead to increased student learning. This may be particularly the case with science (and mathematics) in view of the relatively weak background of the general public in these areas and the relatively little amount of time devoted to these areas in primary teacher preparation programs.

Thus all the PROM/SE curriculum coherence efforts occurred in the context of teachers learning more about the science topics

already being taught and assessed at various grade levels. However, the introduction of the “8+1” concepts provided teachers a way of obtaining more than a simple grasp of the facts they must teach students; it provided them with a conceptual foundation that connected the topics in their curriculum. This

conceptual foundation creates coherence among the topics any one teacher might teach in a particular year – what we’ve termed micro-coherence – as well as among the topics students encounter from one year to the next (macro-coherence). Both are important if students (and teachers) are to begin to move beyond any set of particulars studied and develop an understanding of science, a way of making sense of the natural world that can lead to a scientific literate mindset.

A critical part of the PROM/SE teacher professional development was to work with the districts’ science curricula and instructional materials from the perspective of the “8+1”. A sub-group of the research scientists and science educators worked

with teachers to help them understand these concepts through content-rich explorations of the topics they teach. Once familiar with the “8+1”, teachers then worked to elaborate how each unit in the districts’ science curriculum at a specific grade related to these fundamental concepts. The lessons were then enhanced to include a description and/or demonstration of the role of the pertinent fundamental concepts in each lesson. The ordering of units and lessons was determined by each district’s curriculum whether that was based on local, state, or national standards. The process for enhancing lessons that have been linked to the fundamental concepts proved to be equally helpful to districts that were maintaining their adopted curriculum and those that were in the process of transitioning to new science standards. Once linked and enhanced, units and lessons could be moved and reordered on the web-based system as needed, to address the district’s adopted standards. In other words, each unit can be thought of as a story with details related to some aspect of science. It is not the details that are the central focus of the story, but it is the linkage to the underlying and deeper fundamental concepts. As with good literature, the details of the story line may be lost over time, but the deeper societal and life related issues remain. So it is, we propose, with science. Being scientifically literate is to have a deep understanding of those “8+1” concepts even if you cannot remember the details of some scientific

facts. This work involved research scientists working with the teachers and curriculum directors for each of the districts.

SOME FURTHER IMPLICATIONS

This approach to bringing coherence to school science holds promise not only with respect to the science curriculum but also for teachers who often struggle to make sense of the shopping list of topics found in standards and textbooks. One of the rewards the scientists and science educators who have led the PROM/SE science professional development workshops have had is seeing the “light bulb go on” for teachers as they have moved beyond a simple grasp of one of their instructional units and have begun to see how it fits within a greater, deeper scientific view of the natural world as they begin to grasp the many connections among the “8+1” and their instructional units. Furthermore, they begin to understand that there is a deeper more important – but often hidden – story or unit, which in effect connects all the little units or science topics that they thought were unrelated to each other. The work of elaborating the connections of these fundamentals to their instructional units is difficult and challenging for teachers as this is not the usual mode of thinking either for them or for their students. Nonetheless, it is work the teachers have found rewarding and helpful in improving instruction.

The conception of coherence and science literacy developed here has implications

beyond instruction in schools and classrooms. One of the goals would be to have students achieve the holy grail of learning, i.e., to apply what they know to new and novel situations. If students (and teachers) become conversant with these fundamental science concepts, as science literates they most likely will be able to apply these concepts to natural phenomena that they have not encountered before. In as much as science is an ever-expanding domain of knowledge about the natural world, this sort of flexible critical thinking is crucial.

How would one assess whether this sort of flexible knowledge has developed? Such an assessment would of necessity have a focus not on the facts that were to have been mastered but on the concepts and principles behind those facts and an extension of them into novel territory; an hypothesis/explanation building exercise around some novel set of observations/facts. It would require a concerted effort to develop this type of assessment as this is substantially different from any current measurement instrument (See Figure 4). Nonetheless, a few such prototype items were developed by the PROM/SE science working group and piloted with teachers at one of the PROM/SE professional development workshops with some encouraging results. At the outset of a day and a half professional development session, none of the almost 30 teachers could explain

various descriptions of natural phenomena in terms of the “8” fundamental concepts; nor could they propose investigations related to these phenomena. However, at the conclusion of the session devoted to an explanation of the “8+1” concepts, most of these same teachers were able to explain the situations through the use of the “8+1” with varying levels of success.

Finally, the “8+1” approach to achieving coherence in school science also has implications for the preparation and training of new teachers – and not only for new primary teachers. The benefit of this

Figure 4: Example Assessment Item

We must have green plants to survive.

1. *Guided by the 8 + 1 fundamental science concepts, how does science explain this?*

People live in places where there are no green plants.

2. *Generate some possible explanations and support these using the science fundamental concepts.*
3. *Propose some investigations to explore your explanations.*

approach for all teachers is in making explicit important conceptual linkages among science topics. These links between what may be taught in any one year or class to what is taught in another is valuable both for each teacher’s own deep understanding and appreciation of what they teach but for their understanding of how what they teach is related to what students will be expected to learn in other years and classes. This is a valuable professional perspective that is not easily developed whether or not they have

a strong science background. Employing the “8+1” approach to building coherence in school science would be a fruitful way to organize the training of new science teachers at every grade level, as it would provide new teachers with a way to organize and make sense of newly encountered curricula. In a way, the “8+1” fundamental concepts provide a flexible professional development framework that newly trained teachers could apply with the current standards and instructional materials that are extant in any state or district.

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¹ The group included: William Schmidt, George Leroi, Simon Billinge, Audrey Champagne, Richard Hake, Paula Heron, Leon Lederman, Lillian McDermott, Fred Myers, Roland Otto, Jay Pasachoff, Carl Pennypacker, and Paul Williams. See Appendix I.

² Three versions of these fundamental concepts have been created in age-appropriate language for science instruction for students at the elementary, middle grades, and high school levels. See Appendix II.

³ Figure 3 is only one illustration of how the fundamental concepts could be used in connection with an instructional unit to foster coherence in science instruction. Figure 3, out of necessity, is brief and uses science language appropriate for students at the upper elementary level. The risk in this illustration is the perception that the 8 fundamental concepts exist in separate “silos”, a perception we do not wish to encourage but is an artifact of the shorthand adopted for brevity’s sake. Coherence emerges as topics/units are connected using the “8+1” but also as connections are made across the fundamental concepts as applied to any specific unit. For example, the concept of a “system” is an essential part of concepts 4-8 as these have been formulated as responses to the question about systems. However, atoms, molecules, cells, and organisms from concepts one and two are also complex systems and, as such, must be understood in light of the other concepts.

⁴ See Appendix I for authors’ affiliations.

APPENDIX I – PROM/SE Science Working Group

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APPENDIX II

Figure A.1. Fundamental Science Concepts Poster for Elementary Grades



The poster features a collage of science-related images at the top, including a molecular model, a globe, a waterfall, a person jumping, a child blowing a bubble, a field of flowers, a blue energy burst, a sun, and a beach. Below the collage is the title "Fundamental Science Concepts For Elementary Grades". The poster is organized into sections with icons and text:

Inquiry

 How do I know what I know?
How do I know what I need to know?

What are things made of?


 **Atoms:** Big things are made of smaller things.

 **Cells:** There are a vast number of different types of plants and animals.

 **Radiation:** Radiation is everywhere. Light is a form of radiation.

How do systems interact and change?

 **Systems Change:** A system is a bigger thing made of smaller things that can change over time.

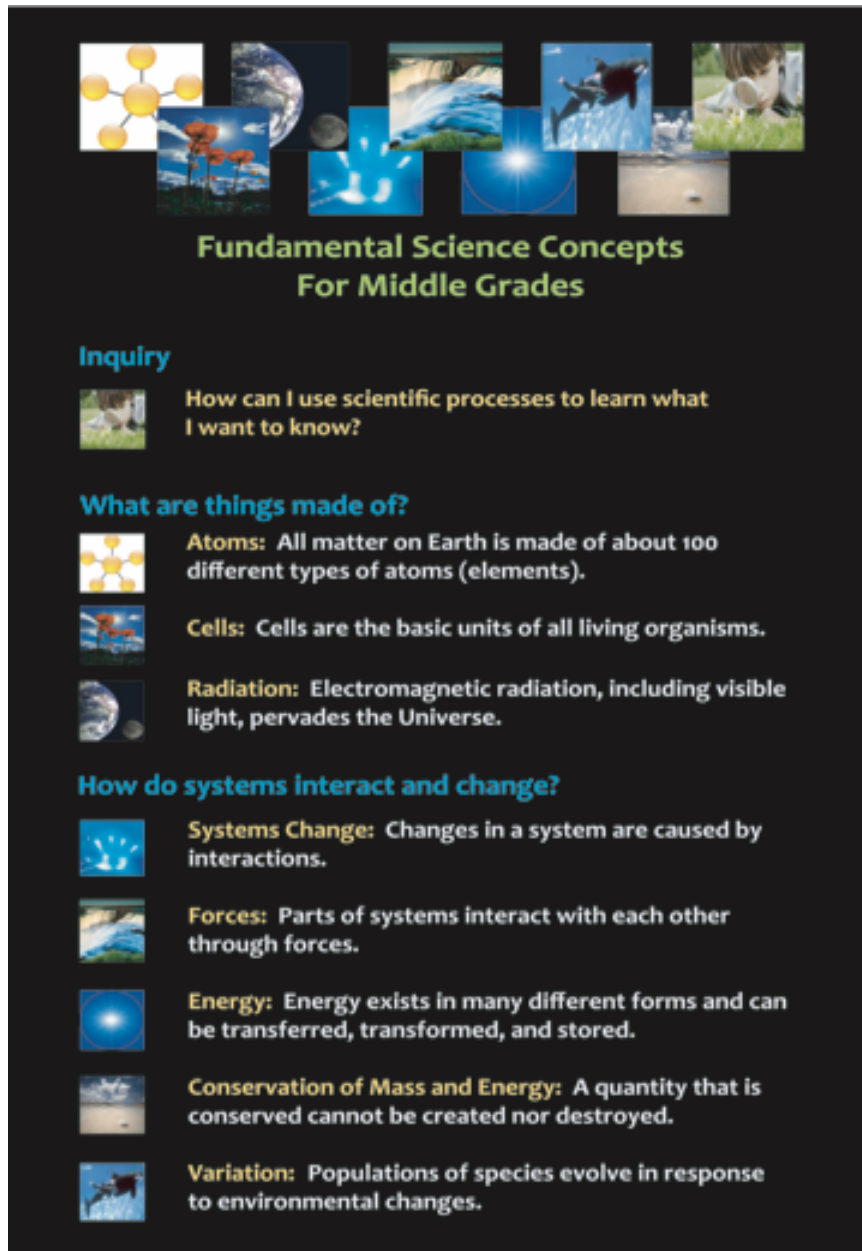
 **Forces:** Changes in the motion of objects are caused by forces.

 **Energy:** Everything that happens involves energy.

 **Conservation of Mass and Energy:** Sometimes matter changes how it looks and feels, but it seems to exist forever.

 **Variation:** Offspring are mostly similar, but not identical to their parents.


Figure A.2. Fundamental Science Concepts Poster for Middle Grades




The poster features a collage of science-related images at the top, including a molecular model, a globe, a waterfall, a person jumping, a child blowing a bubble, a cell, a radiation symbol, a sun, and a beach. Below the collage is the title "Fundamental Science Concepts For Middle Grades". The poster is organized into sections: "Inquiry", "What are things made of?", and "How do systems interact and change?". Each section contains a small icon and a text box explaining a scientific concept.


Fundamental Science Concepts For Middle Grades


Inquiry

 How can I use scientific processes to learn what I want to know?


What are things made of?


 **Atoms:** All matter on Earth is made of about 100 different types of atoms (elements).


 **Cells:** Cells are the basic units of all living organisms.


 **Radiation:** Electromagnetic radiation, including visible light, pervades the Universe.

How do systems interact and change?

 **Systems Change:** Changes in a system are caused by interactions.

 **Forces:** Parts of systems interact with each other through forces.

 **Energy:** Energy exists in many different forms and can be transferred, transformed, and stored.

 **Conservation of Mass and Energy:** A quantity that is conserved cannot be created nor destroyed.


 **Variation:** Populations of species evolve in response to environmental changes.

Figure A.3. Fundamental Science Concepts Poster for High School



The poster features a collage of science-related images at the top, including a molecular model, a globe, a waterfall, a person surfing, a child blowing a bubble, a field of flowers, a blue energy field, a bright sun, and a beach. Below the collage is the title "Fundamental Science Concepts For High School Grades". The poster is organized into two main sections: "Inquiry" and "What are things made of?". The "Inquiry" section includes a question "How can I test my ideas about the world?" with a small image of a person in a field. The "What are things made of?" section lists three concepts: "Atoms" (atoms combining to form molecules), "Cells" (organisms made of cells), and "Radiation" (radiant energy pervades the universe). Below this is another section titled "How do systems interact and change?" which lists five concepts: "Systems Change" (complex systems change according to simple rules), "Forces" (behavior driven by forces), "Energy" (transfer, transform, and store energy/mass), "Conservation of Mass and Energy" (only a few quantities are conserved), and "Variation" (genetic variations and natural selection enable evolution).

Fundamental Science Concepts For High School Grades

Inquiry

 How can I test my ideas about the world?

What are things made of?

 **Atoms:** Atoms combine in different, but predictable ways to form molecules, chemicals, and the wide array of materials that exist.

 **Cells:** All organisms are made of cells which are structurally and functionally similar.

 **Radiation:** Radiant energy pervades the Universe.

How do systems interact and change?

 **Systems Change:** Complex systems change and/or evolve according to a small set of relatively simple rules.

 **Forces:** The behavior of matter and systems is driven by forces.

 **Energy:** Systems can transfer, transform, and store energy/mass.

 **Conservation of Mass and Energy:** Humans discovered that only a few quantities are conserved.

 **Variation:** Genetic variations and natural selection enable life systems to evolve in response to many environmental changes.

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