How does cognitive development inform the choice of core ideas in the physical sciences?

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Introduction

One cannot start answering the question in the title without also considering what else, beside cognitive development, should inform the choice of core ideas. Thus we will rephrase it as two questions: (1) What makes something a core idea for the standards in the physical sciences? And (2) How do cognitive development theories and research interact with other considerations to establish these core ideas? We will consider different candidate criteria that core ideas have to satisfy if they are to be the basis for improved standards, and how cognitive developmental considerations leads us to qualify and revise those criteria with respect to each other. As any concept, "core idea" is not something that is out there, ready to be picked once we establish the list of its necessary and sufficient features; core idea is a construct that takes its meaning from a theoretical approach in which cognitive development plays a central role.

Please note that the reason we are restricting our paper to the physical sciences is not because the ideas we develop are not applicable more broadly, but because all our examples, and our own work, are in the physical sciences.

The first two criteria are about what makes an idea *importan*t from a scientific point of view. The third criterion is that core ideas should make the curricula generated on the basis of standards likely to be effective—i.e., curricula that allow students to really understand it. We will argue that cognitive development is centrally involved in qualifying and concretizing *all* three criteria.

- Criterion 1. Core ideas used in the standards should be deemed **important physics ideas by scientists.**

The most obvious candidates for the meaning of "important scientific idea" are the **tenets of** important scientific **theories** (e.g., atomic-molecular theory, classical mechanics**)**, important scientific **concepts** (e.g., substance, energy, heat) and some **laws and principles** (e.g., conservation of energy).

> Interaction with Criterion 3. One crucial issue, of course, is: Which tenets of which theories? Which concepts? Which principles? **Fewer than are presently taught,** The poor scientific knowledge of the majority of American high school graduates can undoubtedly be improved with innovative teaching methods but no pedagogical changes, however successful, will allow the majority of students to really understand and be able to apply all major scientific theories. When we analyze learning scientific ideas from a cognitive point of view, we start understanding that and why real understanding takes time. Thus, choices of topics will have to be made: Can this important physics topic be taught at all by or in high school? And if

so, in what form and to what depth? We return to this issue and show that cognitive development can inform those choices.

We will also revise the list of candidate types of core ideas after reviewing Criterion 3 below. What we call "stepping stones" qualify as core ideas according to Criterion 3. They are actually central to effective learning. Yet they are not always what comes to physicists' mind when they are asked about important ideas in physics. We will therefore end up with two kinds of core ideas—**core scientific ideas** (those that most physicists would agree are important and correct from a scientific point of view) and **stepping stones,**

- Criterion 2. Core ideas used in the standards should be important for high school students to know whether or not they plan to major in the sciences in college. I.e. core ideas need to be components of **scientific literacy**.

  Interaction with Criterion 3 .To what depth those ideas should be taught is an issue addressed later in the paper as well.

- Criterion 3. Core ideas also need to insure the **learnability** of the curricula designed according to the standards. They do so by providing **horizontal and vertical structures to the standards** .We will argue further that those structural constraints are not deducible from the nature and structure of the expert ideas but from applying conceptual analyses to data from empirical studies on students' ideas and learning; i.e., the source of those constraints is in cognitive development.

We will now examine Criterion 3 and its implications for the nature of core ideas in more detail, coming back to the other criteria later. Our considerations are based on one of our theoretical assumptions—a useful way to understand and improve learning is science is to think of students' ideas on a topic (matter, mechanics, energy) as a large and interconnected knowledge network. (This assumption will be fleshed out as we go.) To anticipate: learnable curricula need coherence and continuity. Horizontal coherence is needed because (a) students' initial concepts, epistemology, and mathematical knowledge are deeply different from scientists' and thus need to change deeply; (b) concepts "meet the world" as a group, and cannot change in isolation; and therefore (c) curricular units need to focus on more than one knowledge element at a time. Vertical coherence (continuity) is needed because (a) each partial change in the knowledge network requires careful tuition and its own context of inquiry and (b) most partial changes have other changes as prerequisites; so that (c) the same concept needs revisiting in different contexts, in different combinations with other knowledge elements and (d) at different points in time.

Grasping the meaning of scientific statements (e.g., matter has weight; to each action there is a reaction) (almost?) always involves **reconceptualization**. Learning that matter has weight is not learning a new relation between existing concepts (as when an educated adult learns that the rate at which jobs are lost is slowing down. "Matter has weight" is not a new fact; rather it embodies reconceptualizing both weight and matter, a process that involves modifying the relations between weight and several other concepts, between matter and several other concepts, as well as new epistemological beliefs and new mathematical and symbolic abilities (particularly measuring, using external representations to represent measurement and reason about quantities, and modeling).

Imagine a child trying to make sense of the slowing rate of job losses. For her, jobs are things like washing dishes, drawing, and putting your shoes on (doesn't Mom say "Good job!" in those contexts?). Things one loses are toys and car keys, not jobs. And what does "rate?" mean. Part of developing a new concept of job is to learn that jobs can be lost, that job loss can be viewed on a national, statewide or regional scale, that people care about such issues, that one needs a job to make money and one needs money to survive, and so on. Note that the meaning of "job" and the meaning of "lose" are co-dependant, i.e., they are part of each other's meanings and thus need to co-develop. The child also needs to develop an important mathematical concept, rate.

This type of reconceptualization is sometimes referred to as "**radical conceptual change**." It is "radical" because, from a cognitive point of view, the change in one concept or in the meaning of one statement can be understood only as part of the changes in a whole network of concepts, beliefs, epistemological and mathematical knowledge, ontological commitments and explanatory schemes. It is also "radical" because the states of the network is profoundly different before and after reconceptualization. Philosophers and historians of science refer to such states as being **incommensurable**. But "radical conceptual change" does not imply learning involves sudden, shifts in student thinking. As we will argue, "radical conceptual change" is consistent with a steady, step-by-step learning approach,

Let us go back to weight and matter to illustrate the "radicalness" of the learning that needs to take place to understand "all matter has weight." Many elementary school children believe that some materials (e.g., Styrofoam) and all small pieces of any material do not weigh anything because, for them, weight is "measured" by hefting. They also do not have a concept of matter, only a concept of different materials, which typically includes only some solids and liquids, but may also include heat, light and other things that one can see, feel, or touch. The reconceptualization involved in understanding the statement "all matter has weight" is extensive; it includes an ontologically different concept of weight (from a perceptual property of objects, centered on the perceptual experience of "feeling heavy" to being an objective property, related to the amount of matter in the object), a change in epistemology (unaided senses are not as reliable as measuring instruments); understanding the nature of measurement; using symbolic means to represent measures and reason about them (the weight measure line), changing the structure of the concept of weight (heft becomes peripheral and is accounted for by weight on a scale and how heft relates to it); mental models and thought experiments ("if I imagine this chunk of clay cut into smaller and smaller pieces, each piece has to weigh something since they make up the whole"); and developing the concept of matter, an extensive process in its own right. Developing a concept of matter includes developing the conservation of substance identity during melting and freezing and the concept form of matter, instead of thinking of state as an intrinsic property of materials; developing the conservation of amount of stuff during melting and freezing, and coming to conceptualize gases as another form of matter. Many of those changes are interrelated. For example, establishing the conservation of stuff during melting is done by weighing it before and after the transformation. Thus learning that matter has weight is not learning a statement, but looking at the physical world through a *very different lens*. Moreover, looking at the world through this new lens requires adopting beliefs that are very counterintuitive—s small piece of Styrofoam and a rising balloon have weight; gases are the same sort of thing as liquids and solids, and fundamentally different from heat and light. This is the case in other physics domains: the idea that the ground is pushing on one's feet is as counterintuitive as believing a tiny piece of clay has weight. The only way to make sense of those statements is to develop very different concepts—weight is not heft, force is not perceived effort. And developing those new counterintuitive concepts is a long drawn enterprise—they have to be constructed on the basis of students' initial conceptualizations, into something that is very different from them.

The previous section illustrates another facet of reconceptualization-- concepts take part of their meaning from their relation to other concepts. This means that achieving reconceptualization requires working on **more than one concept at a time** and therefore the standards need horizontal coherence. As Schmidt, Wang, & McKnight (in preparation) discuss in their international studies of the science education, this is something that the highest achieving nations do remarkably well. Overall the science curricula of these nations are more logically and conceptually organized.

Horizontal coherence also applies to mathematical and epistemological knowledge. We mentioned before that reconceptualizing weight requires the measurement of weight, not just knowing the rote procedure of using a balance scale. This involves understanding the principles of good measurement (e.g., all units have to be the same) and believing that measurement is more reliable and can be more precise than evaluating a quantity with the unaided senses; and understanding that fractions are numbers too, i.e., developing the concept of rational number, and relating counting and measuring.

Clearly, developing a scientific understanding not only of a theory, but of each concept within it, requires lengthy curricular units. It also requires **revisiting the same concept several times**, in combination with different concepts and epistemological ideas, in the context of different kinds of activities, and with different goals, which include integrating partial relations between concepts (e.g., the relation between weight and material with the relation between weight and volume); generalization (from amount of stuff is conserved when a chunk of solid is ground to amount of stuff is conserved during any physical transformation); moving from qualitative to quantitative relations; and developing more complex models (moving from a particulate model to an atomic-molecular model of matter).

Many scientific ideas have other scientific ideas (content or epistemological) as **prerequisites;** in other words, the reconceptualization of some concepts depends on the prior reconceptualization of other concepts. For example, we have found that many third-graders do not differentiate between area, perimeter and volume. These students need to get a qualitative sense of volume as occupied 3-D space before tackling volume measurement and the idea that pieces of stuff of any size occupy some space. In the Inquiry Curriculum, the concept of weight is also revisited multiple times. Learning to measure weight and to represent weight measurement on a weight measure line can lead students to differentiate explicitly measured weight from felt weight and to discover that pieces of stuff of any size weigh something, as they repeatedly divide a piece of clay in half, and consider where each piece might go on the weight line. The relation between weight and material is first explored in contexts in which all objects being compared are the same size (the steel object is heavier than the wood object,) and its relation to volume is explored with liquids first, to facilitate measurement, and in contexts in which a single material is used (larger objects are heavier than smaller ones,). The relation among weight, volume and material is generalized when students explore objects of different sizes and different materials; they learn to differentiate "being heavy" from "being heavy for its size" and to relate "being heavy for size" to the material an object is made of. This qualitative relation could be quantified at a later point when the relation among weight, volume and density is explored. Weight and material are related in a different way in the context of melting--the constancy of weight before and after melting is used to establish that the amount of material has not changed. Weight, volume, amount of stuff, and density are revisited in the context of a particulate model of materials, which is first introduced in the context of dissolving salt in water and used to account for the materiality of gases.

It should be clear by now that developing effective, i.e., learnable curricula involves careful horizontal and vertical orchestration, i.e., decisions about which knowledge elements to include in a curricular unit and in what context, and about how to sequence those units. Core ideas should structure standards so they guide such curricula. We believe that the **learning progression (LP) approach** to science learning, to which we now turn, can help construct a concept of core idea that meets Criterion 3 and make it more concrete. The LP approach also will help us start answering the question we asked about Criterion 1, i.e, which theories and within a theory, which core scientific idea should we privilege?

Learning progressions

In order to make a cogent argument for the relevance of the LP approach to identifying useful core ideas for the standards, we need to look at learning progressions in some detail.

Building on the seminal work of Smith, Wiser, Anderson, & Krajcik (2006) and Catley, Lehrer, & Reiser (2005) on learning progressions for matter and evolution, the authors of *Taking Science to School* proposed it might be productive to link curriculum development to long term *learning progressions,* which they defined as "descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time" (National Research Council, 2007)." The terms "lower anchor" and "upper anchor" refer to the point students start from and the targeted scientific understanding of the topic, respectively (Mohan, Chen, & Anderson, 2009). Several LP's have been proposed for some of the physical sciences.

Our own work on a Learning Progression for Matter (LPM) started from conceptual analyses of middle school and high school students' difficulties with the tenets of the atomic-molecular theory of matter (AMT). For example, the belief mentioned earlier that very small pieces of material weigh nothing makes atoms problematic: what is their ontological status, and how can they be the sole *components* of matter? We interpreted this belief within a broader knowledge network, including the epistemological belief that "our (unaided) senses tell the truth about the world" and the lack of solid understanding of measurement. We traced many difficulties with AMT to incomplete mastery of core macroscopic concepts—weight, volume, density, material-- as well as epistemological obstacles (Smith et al., 2006). In a later paper, we offered rich evidence for the role of macroscopic and epistemological knowledge in understanding vs. misunderstanding AMT, as well as for the inter-relations among students' physical, mathematical, epistemological, and symbolic knowledge of matter at the macroscopic level in middle school.(Wiser and Smith, 2008). In the same way that students' difficulties with AMT can be traced to their ideas about matter at the macroscopic level, epistemology, and mathematical knowledge, so middle school students' difficulties about matter at the macroscopic level can be traced to earlier knowledge about objects and materials and epistemology in childhood, and then to preschoolers', **reaching back all the way to infancy**.

The childhood segment of our progression on matter is based on existing empirical studies with infants, toddlers, preschoolers, and elementary school children but is nevertheless hypothetical in many ways because those studies are few, and none is longitudinal. We are currently engaged in filling some of the gaps in our empirical knowledge (Wiser, Citrin, Drosos, & Hosek, 2008).

Our learning progression is the progression of large, densely connected network of physical concepts (e.g., weight, volume, material, molecule), relations between concepts (e.g., the weight of objects depends on the materials they are made of), including ontological commitments (gases are not the same sort of things as solids and liquids, objects are different from the space they occupy) and causal explanatory ideas (objects push on objects underneath them because of their weight); mental models (e.g., lighter materials are envisioned as made of stuff that is less packed than heavier materials); and categorization principles (specific materials have specific textures and smells). The network also includes epistemological commitments—ideas about how one acquires knowledge and what counts as good evidence for claims (e.g., the way to evaluate the weight of an object is to heft it). Finally, mathematical conceptualizations interact with and constrain the conceptualizations of physical entities and events. We gave examples earlier of some of the constraints different elements of the network place on each other.

Young children's ideas about materials and objects are deeply different from scientists—not only do atoms and molecules play no role in their understanding of the physical world, their macroscopic concepts and ontological commitments are deeply different, and related to a very different epistemology. We gave some examples of the contrast between children's and scientists' conceptualizations earlier in the paper.

And yet, some students end up mastering AMT, and some of those become physicists. Therefore, there is a road from infants' perception and conceptualization of objects and materials to AMT, although it is the road not taken by most American students. Our LPM is a hypothesis about what that road looks like. It is *hypothetical* in a deeper sense than relying on insufficient empirical evidence—it is an **idealization.** We contrast our LPM *to individual learning trajectories* characterizations of how particular students' knowledge evolves in time. Individual trajectories are closely tied to learning experiences and individual characteristics; most importantly they don't necessarily end with a scientific understanding of the targeted big idea, nor even move toward it. A particular student's knowledge evolves as he or she attempts to make sense of what is being taught. These attempts may result in increasing incoherence and truncated growth, rather than achieving scientific understanding. Most students develop idiosyncratic beliefs that may or may not be dispelled later on, as documented by the enormous body of literature on students' misconceptions. In contrast, a learning progression, by definition, bridges a the scientific version of a big idea to the intuitive ideas children develop about it before formal tuition

Both learning progressions and learning trajectories are research-based. but learning progressions 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 if students are exposed to *appropriate* curricula. In other words, both learning progressions and learning trajectories make use of data on students' ideas and performances as a function of instruction but learning trajectories say "This is the succession of knowledge states you will find in students taught with curriculum X and this is the succession of knowledge states you will find in students taught with curriculum Y." In contrast, a learning progression says "on the basis of extensive and intensive cognitive analyses of patterns of beliefs within students exposed to curriculum X, and between students exposed to different curriculum, and on the basis of our theoretical approach to conceptual development, here is a way knowledge could evolve, *given the right curriculum.* That is why a learning progression can be used as a basis for curriculum development. It invites curriculum developers to design curricula that will bring the learning progression about. In contrast, learning trajectories capture the effects of different, existing curricula.

LPM bridges young children's knowledge about matter to AMT via a series of "radical reconceptualizations." This theoretical view of conceptual development was introduced earlier. Its name could mislead: it does not imply that children experience sudden "Gestalt switches" and wake up one day with a different conceptualization of objects and materials; rather, it implies that if one compares snapshots of their matter knowledge network at different points in time, on a large time scale (several years), the two networks will be radically different. But the road between the lower and the upper anchor is a flight of steps. How high the steps are depends on the time scale at which one examines students' knowledge. In other words reconceptualizations are radical only at a large time scale.

We have some empirical evidence that a better macroscopic understanding of matter makes AMT easier to learn (Lee et al, 1993; Snir et al., 2003), but further tests of this hypothesis are still needed through comparative longitudinal studies. In addition, data from an on-going three-year longitudinal study of the Inquiry Project suggests that an elementary curriculum based on our LPM is fostering better macroscopic understanding weight, volume and material, than a traditional curriculum. This evidence is admittedly still extremely limited but encouraging for a LP approach to curriculum design and, within LP approaches, for one emphasizing cognitive analyses and translational constructs centered on concepts, beliefs, epistemology, mathematical knowledge, and the constraints they place on each other.

Thus, LPM makes clear that a scientific understanding of some core scientific ideas about matter at the macroscopic level are prerequisites for making sense of AMT, and also that many students lack this understanding. A view of matter at the macroscopic level consistent with the scientific view is important in its own right and so is the issue of which parts of it should be in the standards. However, in this paper, we want to focus more specifically on the core ideas in AMT and the ideas about matter at the macroscopic level that are core ideas because they are necessary to understand AMT or to motivate it. This is the topic of our next section.

The role of LPs in selecting and formulating Core scientific ideas. AMT

AMT is a *theory* about a *domain* (matter). Its basic tenets are few and simple and its explanatory power is enormous. It is the basis for other major physics theories (in thermodynamics, quantum mechanics, electro magnetism, chemistry) and to other scientific disciplines (astronomy, geology, biology). Feynman writes:

> ”If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* (or the atomic *fact*, or whatever you wish to call it) that *all things are made of atoms - little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.* In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied. (Feynman, Leighton, & Sands, 1963, chapter 1, page 2)

Thus it is clear that AMT is a particularly important physics theory and this needs to be reflected in the standards. AMT is one of the most important scientific theories in part because it provides deep and satisfying answers to questions we all ask about the world around us:

- What are things made of and how can we explain their properties?
- What changes and what stays the same when things are transformed?
- How do we know?

Children ask those questions too, and have some answers, although profoundly different from scientific ones. If the core ideas about matter in different grade ranges are selected, grouped, and formulated as to answer the three questions above, t they will provide continuity to the curricula and help students connect school learning with everyday phenomena they observe. The core ideas should also make the curricula learnable. We propose that the following core scientific ideas for AMT:

a. All matter that we encounter on earth is made of fewer than 100 kinds of atoms.
b. All atoms have mass and take up space.
c. Atoms are always in motion.
d. Atoms are not created, destroyed, or transmuted in ordinary physical, chemical or biological processes.
e. Atoms are bonded together in molecules and networks by electrical forces.
f. The properties of materials are determined by the nature, arrangement, and motion of the atoms and molecules of which they are made.
g. Changes in matter during ordinary physical, chemical or biological transformations can involve changes in the motion, arrangements, interactions, and electrical states (but not the identity) of atoms.
h. The properties of and changes in atoms and molecules have to be distinguished from the macroscopic properties and phenomena they account for.

Together, (a) (b) (c) and (f) answer the first question. (d) and (g) answer the second question. (h) is relevant to the third question. (It needs to be complemented by an understanding of models and modeling). (e) and (c) are included not so much because they are part of the scientific theory (after all, many other aspects of the full scientific theory are not in this list) but because the model is not understandable, usable, or powerfully explanatory without them. We have made the case elsewhere that one of the downfalls of some middle school curricula about the atomic model, is that they do not mention bonds, on the mistaken ground that "one has to keep things simple." But without bonds the model makes no sense—why are we not falling in through the floor, if atoms are discrete entities? Bonds are also necessary to explain the difference between the three states of matter and motion is necessary to explain thermal effects. On the other hand, the statistical distribution of atoms' velocities is not necessary, a point that can be contentious.

Do those core ideas satisfy Criterion 3? I.e., do they insure the learnability of the curricula designed according to the standards they help structure? Not by themselves. To be effective, AMT curricula must build on an adequate understanding of matter at the macroscopic level. And, pedagogically, AMT curricula should elaborate on the macroscopic core ideas studied earlier and provide deeper explanatory accounts of macroscopic properties and phenomena. In the next section we turn to core ideas about matter at the macroscopic level and introduce a distinction between two kinds of core ideas—core scientific ideas and stepping stones.

The role of learning progressions in constructing core ideas about matter at the macroscopic level. Core scientific ideas and stepping stones

We argued earlier that one prerequisite to understanding AMT as a theory of matter was to believe that matter can exist as tiny pieces, and that any piece of matter, however small, has weight and volume. Without that knowledge, atoms cannot be the sole component of matter. We also argued that coming to understand "matter has weight and volume" required radical reconceptualization.

Thus "matter has weight and volume" satisfies Criterion 3—it ensures the learnability of the AMT curriculum. . "Not so fast!" says the physicist "Matter has weight" is not a core idea according to Criterion 1. It is deeply incorrect.! The scientific statement is "Matter has mass. We cannot structure the standards around statements that are incorrect." To which the cognitive developmentalist replies, "The choice is between students learning an incorrect statement "for a good reason," or not learning anything at all!" By that she means that learning that any piece of matter has weight, no matter how small, is a large step toward a scientific understanding of matter—it will allow students to understand AMT and develop a concept of mass. It is a **stepping stone.**

The concept of matter is built by generalization of properties rather than via definition—focusing on *weight and volume as inherent properties of materials* creates an important bridge between solids and liquids on the one hand, and gases on the other, which leads to a new ontology. This bridging provides links between existing and new ideas so that the new idea makes sense, and avoids the destabilization commonly created by simply telling students "solids, liquids and gases are forms of matter" Or worse, "Matter is what has volume and mass."

Stepping stones make a lot of sense within a LP approach. What differentiates two successive states of the knowledge network along LPM is not that one contains more elements of the expert theory, or that it resembles the expert theory more closely. It is rather, that the structure and content of each state is such that, with the support of carefully crafted curriculum and effective teaching, the next one will put students in a better position, eventually, to understand a basic version of AMT.

In the Inquiry Project, "any small piece of stuff has weight" is an explicit target of understanding of our 3rd grade curriculum, although not in isolation. It is fostered by a large number of coordinated activities that develop an objective concept of weight: it is a property of objects, independent of the person measuring; it is extensive (i.e., twice as much stuff weighs twice as much); and it depends on the material an object is made of. The activities also target a conceptual understanding of measurement, coordinating measuring weight and representing it on a weight measure line and drawing inferences from it, and a new and important epistemological belief—measuring with an instrument is to be trusted more than using one's unaided senses. In earlier work with middle schoolers, Smith found that there were strong correlations between having the belief that "any small piece of stuff has weight " and developing an understanding density (Smith et al., 1994, 1997). In our current longitudinal study with the Inquiry Project, we are examining whether developing this belief in 3rd graders is correlated with their developing an understanding of density and other important ideas in their matter network later on in grades 4 and 5. That it, we will be explicitly testing the hypothesis that it functions as a stepping-stone.

We suspect that students who achieve those understandings are much closer to a scientific view of matter at the macroscopic level and to eventually understanding AMT than if they had be taught "Matter has mass." The knowledge 3rd graders bring to the classroom does not allow them to make sense of such a statement. Differentiating mass from weight is a notoriously thorny problem in physics education; it requires a solid understanding of mechanics, including that weight is a force, i.e., a relation between two objects involving gravitation. This seems, conceptually, "orthogonal" to developing a basic understanding of AMT. Moreover, our students are developing an important precursor to mass—amount of material-- which is distinct from weight. If and when students take the step of understanding mass and its quantitative and conceptual relation to weight, revising "matter has weight" as "matter has mass" or qualifying it as "matter has weight on earth" should not represent much of reconceptualizing problem. On the other hand, the belief that matter has weight opens the door to investigations about important principles (e.g., that amount of material does not change when a solid chunk melts (by weighing it before and after melting) and other reconceptualizations (e.g., that gases are material, also by weighing them).

Not all of our intermediate targets of understanding in elementary school are scientifically incorrect! Some are core scientific ideas, e.g., "Matter occupies space." Others are scientifically correct without "counting" as core scientific ideas. The extensivity of weight, the notions that the weight of objects depends on what they are made of, that the weight is constant across phase change, and that the identity of a material stays the same during grinding, melting and freezing are also scientifically correct. They may not be *core* scientific ideas but they lead to them— the conservation of mass and of the identity of a substance across physical. changes.

Thus, we want to propose that **stepping stones take their place next to core scientific ideas to structure the standards**. Although they do not satisfy Criterion 1 as being important *scientific* ideas, they are important ideas.

A similar case can be made for a particulate model of matter, which we include in our 5th grade curriculum. (A particulate model is a model that assumes matter consists of different kinds of discretely spaced particles that have characteristic weights, are held together by bonds, and in motion.) Doing so gives students a way to truly explain the processes of melting, freezing, evaporating, condensing, and dissolving, the conservation of amount of stuff and material identity through phase change, and why weight is constant across physical transformations, without having to master all the tenets of AMT. The model is sufficient to account for interesting and scientifically important phenomena. Importantly, it contributes to the an epistemological understanding of modeling. It is a stepping stone in that it allows students to master some of the tenets of AMT (particles are in motion, they are discretely arranged, they are held by bonds), understand its explanatory power, and develop an important epistemological skill, all of which will make AMT easier to master, and more likely to be learned correctly.

Several researchers have advocated beginning with particulate models, which are simpler than the atomic-molecular model, for these or other phenomena (e.g., Children's Learning in Science Project, 1987; Chomat, Larcher, & Meheut, 1988 ; .Johnson, 1998abc, 2000, 2002; Nussbaum, 1997; Snir et al, 2003) and have evidence that these models are not only useful for helping students make sense of important macroscopic phenomena, but for developing their metaconceptual understanding of modeling . Significantly, Snir et al (2003) found that it was the students who had developed sound macroscopic understandings that matter takes up space and has weight that best appreciated the explanatory potential of the model. These examples also speak to another point made earlier: AMT curricula should elaborate on the macroscopic core ideas studied earlier and provide deeper explanatory accounts of macroscopic properties and phenomena.

One issue is which tenets of AMT we want students to understand as part of science literacy and how far to go (K-12). Krajcik's IQWST Chemistry units for 6th-8th graders involve them with developing and using particulate models to ground their understanding of a substance, and physical and chemical change. Further, his group is actively mapping out an ambitious LP for ATM that spans grade 6-college and outlines a progression of more and more complicated models of the atom (starting from atoms as spheres, moving to a basic model of atomic structure that includes protons, neutrons, and electrons, and to more complex models, such as the Bohr model, the electron cloud model, and shell models which represent energy levels). Within their LP framework, they nicely "characterize the development of conceptual understanding multi-dimensionally, and visualize LPs as a progression of sets of ideas instead of isolated strands of knowledge….In this way, LPs can accommodate strategic sequencing that promotes both branching out and forming connections among ideas within and across knowledge domains." (Stevens, Shin, & Krajcik, 2009). Particularly important to their analysis are students' changing understanding of the *relations among core ideas* about elements/periodic table, atomic structure, and electrical forces. Like us, they are trying to map a sequence that distinguishes steps in learning that are *productive* for further learning (and hence may be thought of as meaningful stepping stones) and those that are not. Only steps that empirical evidence suggests are productive intermediate steps are included in their LP.

Defending the pedagogical value of stepping stones is part of a bigger point about LP—the importance of structuring curricula, and by implications the standards, according to cognitively appropriate core ideas, rather than the more traditional top-down approach, informed more narrowly and exclusively by the expert theory and by a logical analysis of the content domain. Too often, the expert theory is broken down into its different component core ideas, which are then taught in different grade ranges, in isolation of each other, and often without being revisited. This creates several problems.

First, concepts are interrelated; teaching about one without taking the other into account not only leaves most students without means for integrating the pieces but, more fundamentally, is a recipe for seriously destabilizing the evolving knowledge network For example, consider the core idea "matter exists in three states, solid, liquid, and gas." This is often taught in the early grades, as declarative knowledge, without taking into account that most young students' concepts of matter and gas are very different from the expert's and that such a statement will leave them at a cross-road about what gases and matter might be. Thus, instead of building on students' implicit matter concept (something one can touch and see), relating the weight and volume of solids and liquids to "amount of stuff," and bringing them to a stepping stone from which they can make sense of the materiality of gases and conservation of matter using weight as evidence, one destabilizes their knowledge about matter completely. Thus, we see building a strong understanding of the materiality of solids and liquids (which includes helping students deeply understand they take up space and have weight) as a stepping stone for learning about the materiality of gases and hence the core idea that matter exists in three states.

In addition, an expert's theory approach will often misjudge the appropriate grade range in which to introduce different concepts or practices, again because it is looking primarily at "final form" practices, and hence misses opportunities to nurture the development of that idea early on. For example, models are central to expert theories but rarely included in elementary and middle school curricula because they are assumed to require sophisticated hypothetico-deductive thinking. However, the work of Lehrer and Schauble (2000) has shown the variety of "earlier" forms that modeling can take in elementary school children. They argue that working on those early forms (including creating initial models that "look like" what they represent) are important stepping stones for building and revising metaconceptual understandings of models. Similar lessons come through in the LP project on modeling (Schwartz et al., 2009).

The role of learning progressions in selecting core ideas. "Privileged LPs"

In the previous sections we have established that one of the main roles of core ideas was to provide coherence and continuity to the standards and by implication, to the curricula they support. We have explored how to select, formulate, and group core scientific ideas so that they answer important questions about the physical world, and made the case that some core ideas have to precede others to either make them understandable, or motivate them. We introduced stepping stones as an equally important source of coherence and continuity for the standards, and of learnability for curricula.

We now return to another issue raised in the Introduction Are some *domains* more "core" than others? Are some *theories* more "core" than others? We propose that matter and classical mechanics should have a special status in the standards. We have already argued that AMT was one of the most important theories in physics and that a macroscopic understanding of matter was also crucial, both in its own right and because it is necessary to learn AMT meaningfully (although it is not a theory). We will now argue that classical mechanics is another privileged theory, for some of the same reasons as AMT, some not addressed until now.

Like AMT, classical mechanics also accounts economically (Newton's three laws) for an extremely wide range of phenomena and is also involved in other major physics theories (astronomy; universal gravitation). Together, the two theories provide answers to the most fundamental (and similar, pari passu) questions one can ask about the physical world: Why do objects move? Why do they stop? Why do they follow the trajectories they do? And: What are things made of? What makes materials different from each other? And also: When materials change state, what changes? What stays the same? When objects move, what changes? What stays the same? As well as to many, many others: Why is the sky blue? How do I send a rocket to the moon? Why do I have trouble getting my car up this icy slope? Why should I believe I will consume less heating oil if I turn my thermostat as low as possible on winter nights? This makes them relevant to wide range of social and political issues, and thus central to science literacy. Thus the tenets of both theories satisfy Criterion 1 and Criterion 2. We have argued that a subset of them also satisfy Criterion 3, and qualify as core scientific ideas.

Perhaps not surprisingly, given science must have started with questions that could be formulated in everyday terms, very young children have some conceptual resources to think about the "big" questions listed in the previous paragraph. Infants' perceptions and conceptualizations of the physical world are constrained and enabled by what cognitive scientists call "core knowledge" [1](see, e.g., Carey, 2009; Gelman & Williams, 1998; Pinker, 2007; Spelke, 2000).). For the atomic-molecular theory, those precursors are knowledge about materials, solids and liquids and weight, as well as the belief that two objects cannot occupy the same location at the same time. Precursors for classical mechanics include a notion of push and pull, mechanical causality (objects can push and pull each other) and a sensory-motor concept of force. Young children have ample opportunity to elaborate on that knowledge as they interact with the physical world and with members of their communities. They enter school with both a rich set of experiences about the properties of objects and materials and the motion of objects and with the motivation to learn more about the "big" questions in elementary school.

Part of their knowledge is shared and constitute what we will refer to as "precursor ideas" i.e., ideas that are related to stepping stones or even core scientific ideas although they need radical reconceptualization. Like core knowledge in infancy did with respect to

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[1] "Core" has a very different meaning in "core knowledge" than in the theme of the present paper "core ideas."

informal experiences, those precursor ideas both enable and constrain children's understanding of science curricula material. LP based curricula can recruit and transform those precursor ideas effectively and productively. In LPM, precursor ideas cluster around weight, material and size.

To our knowledge, a LP for mechanics has not yet been developed, but cognitive psychology and science education research has produced very rich empirical evidence for core knowledge in infants (Baillargeon, 2002; Spelke , 1991) and for extremely prevalent misconceptions in middle school and high school students (Hestenes,Wells, & Swackhamer,1992). Information about preschoolers' and elementary school children's ideas in mechanics is scanter but we predict that, as in LPM, a LP for mechanics will include precursor ideas, perhaps: moving objects have "force" that keeps them moving and enables them to act on other objects and exhaust itself in time; motions are characterized by speed (an undifferentiated mix of velocity and acceleration) and trajectories (straight, curved, up, down); pushing on an object at rest or in motion makes it move in the direction of the push.

The universality of core knowledge and early learning experiences in the domain of matter and motion (all children encounter objects made of different materials in solid, powder, or liquid form; all children throw, drop, carry, and pull objects and observe objects roll down slopes, sink or float, or blow in the wind) makes it likely that precursor ideas in those domains are very similar. The few studies on this topic support this assumption. An interesting question then is: given a single starting point (shared precursor ideas) and a single target point (the atomic-molecular theory, classical mechanics) in how many ways can the knowledge network evolve productively (when characterized at the level of concepts and beliefs)? In other words, how many LPs are there for matter and mechanics? Please remember our view of LP (p.8)—it is about an ideal succession of knowledge states, not about individual trajectories.

This question can only be answered empirically. In the case of matter, we predict that the answer is "only a few," because we believe that the knowledge network can only change productively in very few ways. This is because students' knowledge places major constraints on its own course of development, which come from the numerous connections between knowledge elements. This means that few curricula will successfully bridge the lower and upper anchor. It could be that the same will be the case for mechanics, because of the common characteristics just reviewed.

Another implication of our hypothesis is that matter and mechanics are two domains that are particularly learnable. This would be because core scientific ideas have roots in early childhood; as students' knowledge develops along the LP, this aptly named "anchor" provides a continuous link to the physical world, which contributes to the meaningfulness of the scientific ideas.

If we are right, mechanics and matter are also privileged because, with LPs few in number or even perhaps unique, there will be a principled reason to assign their core scientific ideas and stepping stones to specific grade range.

Finally, they are privileged because they will provide a basis and a source of analogies for the "non privileged" physics domains, thermodynamics and electro magnetism, which, in our view, do not have core knowledge, or precursor ideas and therefore no lower anchor to provide basic intuitions or build upon. We predict that LPs for those domains will be quite different from the privileged LPs; they will rely more heavily on mathematics, epistemology (they will have to rely entirely on modeling), and will get their meaning from analogies. We doubt that their LPs will be as heavily constrained as in the privileged domains. They will share with the privileged domains the construct of stepping stone. The work of White and Frederiksen (1990, 1993) on modeling electrical circuits provide support for what they call "intermediate causal models" which we envision as a major kind of stepping stone.

Not all LPs are about domains: The case for a learning progression for energy

Core scientific ideas and stepping stones can also come from LPs that focus on a concept, rather than a domain. For example, research is being conducted from an LP point of view about emergence, which cuts across physics, biology, and the social sciences. Within physics, several research teams are developing energy related LPs (e.g., Mohan, Chen, & Anderson, 2009). We have started to conceptualize a LP for energy in physics (LPE) but, at this point, can only offer very limited and preliminary insights about its nature and its implications for core ideas and stepping stones.

Although it is a concept and not a domain, energy shares many important characteristics with matter and mechanics. It is one of the most important concepts in science and in scientific literacy; it is relevant to most theories in physics, chemistry and biology, and, we believe, it has precursor ideas (e.g., a basic understanding that "things even out" via exchange and motion; heat is emitted by hot sources; heat causes solids to melt and water to boil; heat makes temperature rise).

Energy might stand alone, however, as being hardest topics to teach in high school and college. As with most scientific concepts, students' ideas about energy are very different from scientists' and require deep reconceptualizations. Energy also poses specific pedagogical problems because it is a very difficult idea in its own right; unlike, e.g., atoms or photons, energy has no physical reality. In the words of Richard Feynman,

> *"there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens."*

One of LPE's focus will be *energy transfer* as a powerful way to characterize how changes within one system cause changes in another system. This contrasts with the focus in the American standards—the *transformation* of energy from one form to another.

We believe that thermal phenomena will play an important role in our LPE; they are familiar to students and are easily spontaneously conceived of as involving *transfer*, and thereby are a good entry point to that concept; Thermal phenomena also involve *change* and often more than temperature change—phase change and thermal expansion. Thus they provide a building block for the idea that energy transfer is associated with change as well as a context in which ideas about matter and ideas about energy can both be integrated and provide stepping stones for each other.

Thermal phenomena also are easily associated with energy *conservation*, a cultural model transmitted to children outside classroom settings, and a crucial aspect of understanding global warming and the need to conserve the earth's limited resources. Finally, thermal phenomena, if modeled at the particulate level, involve changes in *motion* (faster molecules, by interacting with slower molecules make them move faster while they themselves slow down). This understanding is core scientific idea which can scaffold looking at other kinds of energy transfers, such as from object scale motion to molecular motion (friction) or the reverse (steam engine).

Let us not forget Feynman: ontologically, energy is a "book-keeping" entity, which needs to be conserved in closed systems. An important part of our LPE will be epistemology. Given the abstract nature of energy, it is crucial that students learn to be comfortable with the idea of a theoretical construct, and how to use it. Modeling is also central to help students develop visual references for this totally abstract concept. LPE will also involve a mathematics component because studying empirically the conservation of energy requires quantification.

Some of our (very hypothetical at this point) LPE's implications for the standards would be the following. Two early core ideas about energy would about the relation between heat and temperature and thermal equilibration. An early stepping stone would be that cooling is not due to cold coming in but heat leaving (this stepping stone is a scientifically correct idea but it is not an important idea in thermodynmamics; it is crucial to making a curriculum learnable, however, because the "existence" of cold is innately entrenched in a touch system that includes hot and cold receptors). Another implication is that, at some point, and probably relatively early, some core ideas and stepping stones will integrate ideas about matter and energy.

Is LPE a "privileged" LP? This will be better answered once it is in existence. In the meantime, the answer is "yes" and "no." It is privileged for the reasons stated at the beginning of this section. But it may lack the uniqueness and learnability of LPM and the still-to-be created LP for mechanics. As different from scientific ideas as the precursor ideas are for matter and mechanics, energy's precursors are much further away from the scientific ideas. As important as epistemology, modeling, and math are for LPM and mechanics, they will have a bigger role in LPE. And, let us not forget Feynman..

In what grade ranges should core ideas about energy be introduced? Again, it is too soon even to speculate. Wiser & Amin's (2001) work on teaching and learning about heat and temperature suggests that a particulate model may be a stepping stone for the differentiation of heat and temperature and constructing an extensive concept of heat. But our future work might unearth unsuspected macroscopic stepping stones.

How Does Our View Relate to the Current Standards? What are their Strengths and Limitations?

Goals and Overall Organization of Standards: Key insights and two problems

Current national standards (Benchmarks, NSES) took as their main goal trying to establish and codify the diverse kinds of knowledge, skills, abilities and habits of mind that were essential for **scientific literacy**. One of their main goals was to get educators to see that science literacy was not just about learning **science content** in specific disciplines, but also about developing **a sense of the big picture** (i.e., developing a sense of what is science all about, how it relates to them and their world, what it contributes to society via technology and other means, and understanding some of the connections and common ideas across different areas of science) and **scientific habits of mind or skills of inquiry** (how to ask a question, plan an investigation, etc). They were critical of the "overstuffed" science curriculum, which they saw as presenting too many unrelated facts, or too many technical definitions to be memorized, and therefore sought to provide a more principled way to "pare it down" by asking what were the fundamental ideas about science (both within and across disciplines) that were of lasting importance and worth teaching.

In keeping with this main aim and in recognition of the diversity of what was important, they both sought to codify what is important to know, by organizing into **overarching categories of different types** which separately consider important transdisciplinary and metaknowledge about science, historical knowledge about science, dispositions, abilities, and skills that support doing and thinking about science, understanding of science and technology, and of course knowledge of relevant disciplines.

In NSES there are 8 overarching categories, of which only 3 focus on knowledge of specific disciplines (Physical Science, Life Science, and Earth and Space Science). The other 5 concern: Unifying Concepts and Processes, Science as Inquiry, The History and Nature of Science, Science and Technology, and Science and Society.

In Benchmarks there are 12 overarching categories, only 2 of which focus on knowledge of traditional scientific disciplines (The Physical Setting, and The Living Environment). They too have a section on Common themes, Habits of Mind; and History and Nature of Science (as two separate sections) and Technology (the Designed World; the Nature of Technology). In addition, they also include the disciplines of psychology and social science (The Human Organism; Human Society) and mathematics (The Mathematical World; The Nature of Mathematics).

Clearly, the amount of work that went in to identifying, clarifying, and codifying those ideas is staggering. In many cases, the language used to describe these areas has been crafted very carefully and thoughtfully. They certainly are worth studying, and they embody a tremendous amount of "collective wisdom" of different stake-holders: scientists from diverse disciplines, science education researchers, science educators, policy makers, etc.

But as we see it, there were two main problems created by this approach that an LP approach may help solve:

Problem 1: Although the purpose was to "pare down" and deal with the problem of the "overstuffed" curriculum, they accomplished the *paring down within the disciplines* by *adding many other categories*. The result: teaching science still seems overwhelming in the sheer AMOUNT you have to do. How does a teacher or curriculum developer approach dealing with 8 to 12 different categories of things to do, as well as the tremendous amount within the disciplines? Which of the categories is privileged? Inquiry? Common themes? The disciplines or broad domains?

Problem 2: Although the rhetoric of these documents was one of integration and building connections, their organization do not make these connections transparent. For example, each important type of content is presented in its own separate section. Thus, the content standards for knowledge in the disciplines, present the big ideas in static propositional form, not as connected to the other areas. NSES recognizes this problem, and therefore adds vignettes of Inquiry into the content knowledge sections to give the reader a sense of the kind of the classroom dynamics it had in mind for teaching these standards. Benchmarks also realizes the importance of connections, and supplements its documents with Strand maps that try to show the connections among ideas both horizontally and vertically. However these connections are primarily within the discipline specific content standards, not across different kinds of content—mathematics, meta knowledge about measurement or models. In this way, they left the integration to the individual curriculum developers or teachers.

More fundamentally, presenting content knowledge as a separate section from Inquiry or Habits of Mind (even with the expectation that they will be combined in curricula), establishes that the two are independent. This organization is antithetical to the very nature of scientific knowledge—theories are models, concepts *inherently* part of their meaning from measurement.

A related concern is the content of Inquiry skills. By dissociating observation and classification from modeling and hypothesis testing, and relegating the latter to the higher grades, these standards embody the assumption that young children are incapable of modeling and fail to embody the crucial notion that observation and classification is at the service of understanding--to understand why things are as they are, i.e., at the service of generating and testing hypotheses.

Present proposals about core ideas: An important theme of the LP approach is that the development of domain-specific knowledge is inherently linked to meta-knowledge about science, using new symbol systems and forms of representation, engaging in new forms of discourse, etc. For example, the LPs for Environmental Literacy (Grades 4-college) discuss three types of embeddings (worldview embodied in discourse, practices within worldview, and knowledge supported by practices and discourse). In work on the Grade 3-5 LP for matter, the integration of model based reasoning about matter with the development of quantitative reasoning of various forms and meta-knowledge about how we know comes to the fore, along with the importance of key representational tools such as the weight line. In Krajcik's work on Matter LP for Grades 6-12, integration of predicting and explaining across developing big ideas is especially well developed.

Our proposal for core ideas embodies this theme and therefore makes the nature of scientific knowledge more transparent for all grade bands and provides curriculum developers with more concrete guidance about the integration of content knowledge with inquiry skills. The horizontal and vertical structure of our core ideas and the recurrent "big questions" embody the relation between observation, measurement, hypothesis generating and testing, and concepts. (e.g, that the measure of weight is via a scale, not hefting).

A benefit of LP work is that it will not only provide needed models of what such integration can "look like", but may highlight important elements needed in such an integration that are generally overlooked in the existing standards (e.g., mathematics, forms of representation, types of discourse). In the process, certain elements, currently not mentioned at all in the standards (e.g., key representations, mathematics) may come to the fore.

Organizing Content Standards Across Grade Bands: What are assumed core ideas and models of development? Can they promote horizontal and vertical integration?

Another common feature of the Standards is their organization of each major area according to main topics addressed across age bands. This addresses the obvious need of the Standards to provide guidance about what the "top level" ideas are for the content areas and how those ideas develop over time. But what models of the "top level" ideas and development underlie their grade band organization? And to what extent does their organization provide both horizontal and vertical coherence?

Consider first the top-level organization of the Benchmark for "The Physical Setting." There are 7 broad category headings across all 4 grade bands:

Benchmarks: The Physical Setting Standards

K-2	3-5	6-8	9-12
1-The Universe	1-The Universe	1-The Universe	1-The Universe
2-The Earth	2-The Earth	2-The Earth	2-The Earth

3-Processes that shape the Earth	3-Processes that shape the Earth	3-Processes that shape the Earth	3-Processes that shape the Earth
4-Structure of Matter	4-Structure of Matter	4-Structure of Matter	4-Structure of Matter
5-Energy Transformations	5-Energy Transformations	5-Energy Transformations	5-Energy Transformations
6-Motion	6-Motion	6-Motion	6-Motion
7-Forces of Nature	7-Forces of Nature	7-Forces of Nature	7-Forces of Nature

First, we would note the “top-level” organization is one of categories, not core ideas. We would propose that core ideas are beliefs about fundamental relations among core concepts (these can include definition relations, predictive relations, and deeper explanatory relations), which can be formulated in *sentences* (although many are more precisely formulated in mathematical “sentences”). So by this definition “Energy” or “Matter” may be a core concept, but not a core idea. It is important beliefs about energy or matter that for us are core ideas—beliefs about what kind of thing it is, how it interacts with other things, etc. (The problem with simple words is that they can be understood in many different ways; their meaning can change as one’s beliefs develop and change.) Benchmarks does use specific sentences at the next level—which are the explicit standards). But the statements at this level are of widely different generality and importance. Some are truly core ideas, while others are not, and may not be true stepping stones either.

Second, what is the rationale for this particular parsing? For example, why is the Earth considered a separate topic from processes that shape the Earth; or why is motion an entirely separate topic from forces of nature? If we want to go beyond a topics organization of the standards to a “core ideas” organization, these are all issues that need to be addressed. Further, as we argued earlier there should be a principled basis for the choosing core ideas,that reflect the constraints of development (how ideas will develop from precursors over time with supporting curriculum), the science, and the needs of science literacy among our citizens.

Third, we note that the “top-level” category organization looks strongly non-developmental: The fact that the same broad categories are used in unchanging fashion across a broad span of time gives no hint at how they think children’s ideas about these topics will develop and change. In contrast, in our proposal core ideas for successive grade bands are selected so that the earlier ones pave the way for later ones. Some of those ideas will be stepping stones rather than core scientific ideas because a stepping stone might be much more effective as a prerequisite (and as a belief, irrespective of its developmental role) than a misunderstood or non understood scientifically correct statement.

Moreover, young children bring to the classroom precursor ideas in *some* domains but not others. Those domains should be privileged in the early grade band. For example, heat transfer might be appropriate for early elementary grades, but as *heat*, not yet *energy*. More generally, given the restricted time devoted to science teaching in elementary school, it may be more productive to focus exclusively on some top-level ideas (about matter and motion, e.g.) in the early grades, and make sure that the core ideas within those domain are explanatory from the start.

But perhaps their organization is not so much non-developmental, as embodying a general Brunerian view of development--notably, that big ideas can be taught in some appropriate manner at every age—a view that supports creating “spiral curricula”.

Although this assumption is almost certainly true, by itself it is too weak a principle to constrain a science curriculum or bring about strong vertical and horizontal coherence (this would involve additional careful attention to conceptual analysis, and empirically testing assumptions about conceptual inter-dependencies). At best it seems to privilege vertical coherence (revisit the same topics in “higher” form) without sufficient attention to horizontal coherence (always talk about many diverse topics at any age). Of course, the key to concept building is conceptual coherence, not topical coherence. So in principle one could engage with diverse topics, and still get concept building, if the topics were carefully chosen.

Similar to Benchmarks, the top-level structure of NSES is not yet full sentences (those come in the next level), although they do use “phrases” that perhaps provides more hints about the network of core concepts in play in formulating the big ideas. In contrast to Benchmarks, the top-level structure of NSES is more transparently developmental: both the names and the number of categories change across the age bands, highlighting that both form and complexity of ideas changes with age.

National Standards: The Physical Sciences
(Note: Earth and Space Sciences are a separate category)

NSES K-4	NSES 5-8	NSES 9-12
Properties of objects & materials	Properties & changes in properties of matter	Structure of atoms Structure of properties of matter Chemical reactions
Position & motion of objects	Motion & forces	Motion & forces Conservation of energy & increase in disorder
Light, heat, electricity & magnetism	Transfer of energy	Interactions of matter and energy

Indeed, NSES seems to make strong assumptions about what is developmentally appropriate and how development proceeds (i.e., from observation to explanation, and from concrete to abstract). Some of these assumptions, however, are problematic not only from the perspective of current cognitive developmental theory (which assumes that even young children use abstract explanatory ideas to organize their thinking, and that there is no simple concrete to abstract progression, see Keil & Lockhart, 1999), but also from the perspective of creating horizontal coherence (explanatory ideas are needed to bring order, meaning, coherence among diverse facts and observations.)

For example, NSES deliberately advocates delaying instruction in the atomic-molecular theory until high school, on the grounds that students are not developmentally ready for such a complex and abstract theory until this point. Instead, it proposes the idea of chemical reactions be introduced macroscopically, through the macroscopic definition of a chemical substance as defined by its properties (e.g., fixed melting point) and with experiments in which students assess whether or not the identity of a substance has changed using these criteria. However, in a 3-year longitudinal study of middle school students, Johnson (2002) notes that the idea of pure substance made little sense to his students prior to being taught the atomic model, and, more importantly, that students who were told about "melting point test" did not think of using it to determine whether a chemical reaction has produced a new substance. They had no way of understanding *how* new substances would be produced in the first place. On the other hand, he found that learning about atoms and molecules greatly facilitated developing a concept of chemical substance as something whose identity is maintained across phase change, determined by its properties such as the temperature at which it melts and the manner in which it does so, and being part of chemical combinations and decompositions. In other words, it is not that atoms and molecules account for the concepts of substance, compound, mixture, and chemical change already in place, but rather that they allow students to construct those concepts.

We should stress at this point, that in many cases, we think both Benchmarks and the Standards HAVE included important core ideas in their specific standards. However, as mentioned, we are proposing to add some scientific ideas that we think are core (e.g., Matter occupies space), as well as stepping stones (e.g., Matter has weight). We also propose to revise the order in which some core ideas are presented (e.g., solids and liquids before gases.)

Of course, the main goal of the standards is to organize what children should be expected to know at the end of broad age bands (to meet expectations of science literacy) not to provide a developmental account of how they could get there. In this way, the standards themselves, although informed by research, are not empirically accountable or revisable (Corcoran, Moser, Rogat, 2009). In contrast, the goal of current work in LPs is more centrally developmental, theoretical, and empirically testable. That is, the goal is to develop a coherent (empirically tested) account of paths that connect lower to upper anchors. Assessment and revision of the proposed theoretical paths are central to this process.

Overall, then, we propose that if the standards are to be reorganized around "core ideas", then the process of establishing "core ideas" for the different age bands of the standards should involve serious theory building about how children learn these ideas, not just establishing consensus among stakeholders. The advantage of this approach is the promise of having standards that might actually promote better curricula and student learning. The disadvantage is that serious theory building on these issues takes time and has just begun.

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