LEARNING PROGRESSIONS AS TOOL FOR CURRICULUM DEVELOPMENT: LESSONS FROM THE INQUIRY PROJECT

The Inquiry Project, a collaboration between TERC and Tufts University, is a multi-faceted project that involves elaborating a learning progression for matter developing and implementing curriculum and formative assessment for grades 3-5 based on the learning progression, and conducting an intensive 3-year longitudinal study comparing the growth of thinking about matter among students with and without the new Inquiry Project curriculum. The progression is informed by a broader K-12 learning progression for matter (Smith, Wiser, Anderson, & Krajcik, 2006). In this paper, we draw from our work in the Inquiry Project to formulate ways in which designing curricula within a LP framework contrasts with other approaches: (a) organizing curricular units for each grade around core concepts (that are carried across the grades) rather than topics; (b) using core concepts to build knowledge over time (i.e., across grade) rather than aiming for self-contained modules that can be used interchangeably; (c) establishing learning goals in terms of coherent networks of concepts that are *stepping stones* for further learning, rather than in terms of pieces of expert understanding; and (d) fostering reconceptualization in the domain of matter, using *lever concepts* and *linchpins.* Lever concepts exist prior to instruction and bear important relations to other concepts; their reconceptualization helps propel the knowledge network forward. Linchpins are visual models that express the quantificational structure of concepts; they are an important tool of reconceptualization.

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Introduction

Recently, it has been suggested that it may be productive to link curriculum development to long term *learning progressions,* i.e., "descriptions of the successively more sophisticated ways of thinking about a topic[1] that can follow one another as children learn about and investigate a topic over a broad span of time" (National Research Council, 2007)." Several LP's have been proposed for some of the "big ideas" in science—evolution, carbon cycle, and, in our case, the learning progression for matter (LPM) leading to the atomic molecular theory (AMT).

The overall purpose of this paper is to show how LPM informs the 3-5 grade curriculum we are developing and testing in the Inquiry Project. This "translation" process involves a series of theoretical constructs—*concepts, stepping stones, levers, and linchpins*—which structure curriculum design according to the LPM theoretical framework. We will illustrate those constructs, contrast them to other approaches to curriculum development and argue that, as a set, they make LPM an innovative framework for studying and fostering the development of

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[1] We find "topic" a bit misleading. We think of LPs as about *domains* of knowledge.

students' knowledge about matter.

The Learning Progression for Matter (LPM) started from conceptual analyses of middle school and high school students' difficulties with the tenets of AMT. In particular, it linked those difficulties to incomplete mastery of core macroscopic concepts—weight, volume, density, material-- as well as epistemological obstacles (Smith, Wiser, Anderson, & Krajcik, 2006). Wiser and Smith (2008) offer 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.

For example, many students believe that if a chunk of material is repeatedly halved, the pieces eventually will weigh nothing and then disappear entirely. This makes atoms problematic: what is their ontological status, and how can they be the sole *components* of matter? The idea that very small pieces of matter have no weight can in turn be traced to students' belief that weight is reliably assessed by hefting (and therefore very small pieces of material "weigh" nothing)—which in turn is part of an epistemology which includes "our (unaided) senses tell the truth about the world" and no solid understanding of measurement.

The idea that AMT curricula need to take students' misconceptions about atoms and molecules into account is part of any constructivist approach, but LPM ups the ante in two ways. One is to view learning AMT as a broad and deep **reconceptualization** of one's ideas about matter, i.e., as requiring the reorganization of a large knowledge network that includes many concepts and domain specific beliefs as well as mathematical and epistemological knowledge, in particular about the nature of models, the relation between measurements and visual representations and physical quantities. The other is to make the reconceptualization of **macroscopic** level concepts—material, weight, volume, density, energy—central to this reorganization. Students' difficulties with the atomic-molecular model are perhaps not so much with atoms and molecules per se, but with the lack of fit between AMT as a model of matter and their macroscopic ideas about matter, and more generally, between those and scientists' macroscopic ideas about matter.

This means that *elementary school curricula* on macroscopic aspects of matter are as relevant to mastering AMT as middle school and high school curricula about atoms and molecules. They should take into account the concepts of material, matter, weight and size young students bring to the classroom, focus on fostering conceptual change at the macroscopic level, and include explicit instruction about epistemology, especially measurement. For example, learning about balance scales should be viewed not as learning a procedure but as a context in which to learn about good measurement, to privilege weight measured with a scale ("scale weight") over weight evaluated by hefting ("felt weight") and, as a result, to differentiate and relate the two.

Not surprisingly the scope and time frame of these reconceptualizations call for some novel approaches to curriculum design. In this paper, we will reflect on several ways in which basing a 3-5th grade matter curriculum on LPM has influenced curriculum development and implementation in the Inquiry Project. We will focus on four *translational* aspects of our approach that seem most different from other approaches (and that are directly entailed by an LPM approach):

(a) organizing curricular units for each grade around core *concepts rather than topics*[2]*;*
(b) using *core concepts* to build knowledge over time (i.e., across grade) rather than aiming for self-contained modules that can be used interchangeably;
(c) establishing learning goals in terms of *anchors* and *stepping stones* rather than in terms of pieces of expert understanding; and
(d) fostering reconceptualization including using *lever concepts* and *linchpins*

Before we start, we need to touch on two issues concerning LPM—the construct itself and its uniqueness; in other words, what is LPM and could there be more than one? The field is only starting to consider those issues, the answers to which are likely to evolve as empirical work accumulates. This paper is not the place to address them in any depth but a few preliminary considerations might be helpful.

What is a Learning Progression for Matter (LPM)? How Many LPM's are there**?**

One might start by asking what LPM is not. LPM is not an individual "learning trajectory," i.e., the characterization of how a particular student's knowledge about matter evolves in time. An individual learning trajectory clearly depends on a multitude of factors, including specific science curricula, SES, motivation, etc. The larger the grain size (time or knowledge scale), the fewer the different individual learning trajectories but they remain inherently tied to specific learning experiences. For example, many students taught traditional curricula reach "dead ends." Moreover, students develop idiosyncratic beliefs.

LPM differs from an individual learning trajectory in three ways: a) It is a research-based *proposal* for how ideas about matter could *coherently* evolve over long period of time from young children's ideas to the atomic-molecular theory, if students are exposed to *appropriate* curricula; i.e., it is an *ideal path for successful conceptual development about matter*; b) it privileges *concepts* as the most important grain size for characterizing student knowledge; and c) it places heavy emphasis on the constraints placed on the assimilation of new information by the interdependence among concepts and between concepts and mathematical and epistemological knowledge; i.e., it is *structured by* what we know of the *nature and development of students' knowledge*. In contrast, an individual learning trajectory does not privilege specific concepts, depends on the student's specific learning experiences, does not move explicitly toward achievement of AMT, nor necessarily reaches it. It is the way a particular student's knowledge about matter 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 AMT. LPM is *informed* by data about individual learning trajectories as well as theories of conceptual change but instead of resulting from an existing curriculum, it invites curriculum designers to create one that will bring it into existence. If curriculum designers succeed, individual trajectories will then embody LPM.

Our LPM construct is based on a theoretical view of conceptual change that assumes that concepts and beliefs develop from a universal core knowledge which heavily constrains knowledge acquisition in infancy and early childhood (Carey, 2008; Pinker, 2007; Spelke, 2000).

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[2] An example of "topic" is the water cycle. As noted earlier, "topic" has a different meaning than in the definition of LPs quoted earlier.

The universality of core knowledge and early learning experiences in the domain of matter (all children encounter objects made of different materials; solids and liquids; gravity, etc.) insures the universal development of the concepts of object, aggregate (liquid or powder), material, heaviness, and size, although languages, cultures, and specific environments foreground some concepts over others (e.g., the material level of description and the object level of description have different weight in English, Japanese and Quechu'a) and produce different knowledge at the level of exemplars (specific objects, specific materials).

These concepts are of course far less sophisticated than corresponding scientific concepts, but, more importantly, they differ from them in very fundamental ways, making young children's and scientists' understanding of objects and materials incommensurable (at least in a weak sense)[3]. Therefore all students who achieve a conceptualization of matter commensurable with the scientific view have gone through major conceptual changes; those changes, as a whole, are the reconceptualization we introduced at the beginning of this paper.

The question is then: given a single starting point (preschoolers' concepts and beliefs in the matter domain) and a single target point (the atomic-molecular theory taught to adolescents in a majority of countries) in how many ways can the knowledge network evolve (when characterized at the level of concepts and beliefs)?

This question can only be answered empirically. However we predict that the answer is not only not "as many ways as there are curricula" but "only a few," because we believe that the knowledge network can only change productively in very few ways. Within LPM, curricula act in part as *catalysts*: learning does not take place without them, they have to be specific to the knowledge domain and to students' specific state of knowledge at a given time, but students' knowledge places a major constraint on its own course of development. Thus we expect that, in the end, only a few curricula will "fit the bill' and that, concurrently, few LPMs will be identified.

We now turn to the main topic of our paper, how LPM distinctively guides our curriculum design. The four translational aspects are organized in three sections; the first two are addressed together in the first section. The three sections are: make concepts, not topics, the primary organizer and revisit the same concepts in successive units; reconceptualizing learning goals: anchors & steppingstones; and fostering reconceptualization: levers and linchpins—which address the four translational issues mentioned earlier; the first two are addressed together in the first section.

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[3] "Incommensurability" refers to the lack of communication between people who hold different theories because the same terms (e.g., "matter") have different meanings and different referents (Kuhn, 1962). However terms that do preserve their meaning across a theory change can provide a basis for coherently talking about differences in the theories and help make sense of incommensurable terms.

Make Concepts, Not Topics, the Primary Organizer and Revisit the Same Concepts in Successive Units

The centrality of weight, material, matter, volume and density in LPM makes these core concepts good organizers for curricular units. LPM also makes clear that core concepts are complex—they are related in multiple ways to each other, to other physical and mathematical concepts, and to epistemological stances; this whole network of relations is involved in revising one's conceptual understanding. For example, important aspects of reconceptualizating weight are understanding its measurement, differentiating scale weight from felt weight, and reconceptualizing the relation of weight and material, moving from "iron is heavy" to "iron objects are heavy for their size" and then "iron is dense." This requires encountering weight, material, size and density in the same unit, through activities in which they are linked. The depth and extent of the reconceptualization targeted in the Inquiry Project makes it long-drawn, over the whole grade range. Therefore it is important to give students the opportunity of engaging more than once with the core concepts, so they can build, in time, multiple connections, and integrate them into a new conceptualization.

Existing curricula do not reflect this complexity, and tend to reduce concepts, including core concepts, to definitions, formulas, measuring routines, and "one-shot" exposures. Moreover, they do not problematize all the core concepts of LPM. Density is widely recognized as problematic but weight and volume are not sufficiently problematized as concepts. For example, teaching volume is often centered on using formulas, not on giving students a sense of occupied 3-D space, establishing clear distinctions between length, area and volume, and between volume occupied by a certain amount of material vs. volume as the space in the trunk of a car, or the volume of milk in a glass; or volume of granular materials—does the volume change when the gravel is ground into sand?

In the Inquiry Curriculum, the five core concepts are present in each unit, although some are fore grounded and taught explicitly while others are implicit. Weight and material are presented front and center in third grade. As everyday objects are explored, materials are identified and compared. "Density cubes" (a set of same volume cubes made of different materials) are used to compare the merits of hefting vs. using a scale to measure their weights, and to systematize the set of properties that can be used to compare materials (one of them being the weight of the cubes). Having learned the unaided senses are neither accurate nor sensitive ways to measure weight, students are better prepared for a guided discussion on whether very small things can have weight. This is a first step in establishing that weight is a property of matter. Giving meaning to measuring weight with a balance scale reinforces the link between weight and matter, and helps students to view weight as an extensive property. (These points are developed in the Lever and Linchpin section below.) Volume is introduced only briefly at the end of the unit; density and matter remain implicit. Neither the concept nor the word *density* is used but students' attention is drawn to the cubes all being the same size, and the teacher occasionally uses the term "heavy for its size." Thus density starts being scaffolded in third grade, linguistically, as a placeholder, and by being embodied in the set of equal size cubes. We see this kind of "implicit scaffold" as part of helping students to be ready for a new idea later on.

The focus shifts to a variety of earth materials in fourth grade, when volume and material are front and center and "heavy-for-size" is now an explicit object of inquiry as well. Students extend the range of materials they consider—from solid materials to liquids and granular materials--and revisit comparing equal volumes of different materials. As their concepts of weight and volume become more objective, extensive, and more closely tied to amount of stuff, students are challenged to distinguish heavy and heavy for size, comparing samples of different materials that are all the same weight and observing their very different volumes. Students also greatly extend their understanding of volume by devising multiple approaches to the measurement of liquids, that allow them to see how changing shape need not change volume. As their concepts of weight and volume become more objective and distinct, children are challenged to determine which variable is relevant to water displacement—weight or volume. Through devising "fair" tests, they are surprised to learn that it is indeed the volume rather than the weight that is relevant. Students then explore multiple senses of volume as they contrast the volume occupied by granules poured into an empty container (i.e., the level reached in the container) to the volume of water displaced by the granules. The latter provides a preview of "packedness" which will become important when they study density. Finally, earth materials is also a propitious context in which to strengthen the notion that grinding a solid chunk into a powder does not change the identity of a material, and the concurrent distinction between a material and the state it is in. Students can discover that weight is conserved during those transformation, a first step toward the conservation of mass.

The five concepts will once again be present in the fifth grade, with different saliences-- weight and material remain salient while matter (rather than material) is introduced explicitly. Capitalizing on their belief that weight is an inherent property of matter, students explore the conservation of amount of material across physical changes, using weight constancy as evidence for it. The Earth materials theme is expanded to include the water cycle and salinity. Students explore dissolving, melthing and thawing. They are introduced to gases first in the context of evaporation and condensation and then explore the materiality of air. Again, volume and weight can now play an evidential role of the material nature of gases. The large difference in heaviness for size between gases on the one hand and solids and liquids on the other is also addressed. Students also use a displacement argument for air as matter. Just like a brick in water, when they enter a room the air needs to move out of the way.

To summarize: over three years, the Inquiry Curriculum aims to replace hefted weight with an objective, extensive concept of weight which is an inherent property of matter; to differentiate length, area, and volume as distinct meanings of "big" and to build a concept of volume that is, like weight measured objectively, and a property of matter. At the same time, the notion of material is also systematized—specific properties distinguish materials, one of them being how heavy for their size objects made of different materials are; state and material identity are two "orthogonal" concepts; material identity is preserved when a solid chunk is reduced to powder. 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." Students first learn to associate weight and volume with solids and liquids, and, importantly, with the tiniest pieces of materials, as well as with their conservation across transformations in which material remains visible (grinding, melting, freezing). In fifth grade, gases are introduced via evaporation and condensation in a two-bottle closed system in which water in one bottle evaporates and condenses in the second bottle. This context brings to mind the previous transformations; again, they can rely on weight as evidence that evaporated substances continue to exist; they can also rely on their belief that tiny pieces continue to exist even if you don't see them, and have weight and volume, to start making sense of the gaseous state.

The main epistemological themes are that appearances can deceive, that the unaided senses are not reliable ways of measuring physical quantities, and that the principles of good measurement can result in evidence that helps one to understand phenomena. In the Linchpin section below, we address the mathematical main theme—measure lines.

Concepts, epistemology, and mathematics are integrated in each unit and are revisited not only in different units but in each grade. We are not expecting perfect understanding the first time around, but rather solid progress that serves as the conceptual foundation for more nuanced understanding to come in the next unit. This approach also gives students with different learning rates and styles a better chance to benefit from instruction.

This integrated approach to curriculum development is directly implied by the LPM framework: if student knowledge is viewed as a heavily interconnected network of concepts and beliefs, then, to move the network forward without destabilizing it requires learning about relations between physical entities, rather than entities in isolation.

The Inquiry Curriculum provides ample opportunity of extending their scientific reasoning. Third and fourth graders work with macroscopic experiences to understand weight and volume and how to measure these properties. Their experiences provide the critical foundation for thinking about phenomena that are too small to see. With time and directed conversation, students begin to extrapolate from the observable to the non-observable. For example, using displacement experiences in fourth grade to consider whether the water level of a pond will rise when a rock is tossed into it requires students to step beyond their observations. Experiences bridging between the observable and non observable help learners to develop logical reasoning skills in the context of model-based reasoning (i.e., if all matter has weight, then this little piece must weigh something, even if I cannot feel it; if all matter takes up space, then this little piece must displace some water even if I cannot see it;). Advances in logical thinking and model-based reasoning, learning to rely on measurement and evidence, and developing core conceptual understanding of weight, volume, density and matter collectively prepare the learner for robust understanding of the AMT when this concept is formally introduced.

Constrasts with Existing Curricular Approaches

Many elementary science curricula use a "topics" oriented approach in which "water cycle", "weighing and balancing", "rocks and minerals", and "floating and sinking" are central to the curriculum development. Of course, any curriculum that deals with topics is providing some opportunities to learn about underlying concepts. However, privileging topics over concepts, i.e., selecting topics deemed of interest to elementary grade students or teachers has major drawbacks. Foregrounding "facts", experimental procedures, and equations over explanations—water evaporates, wood floats, different processes produce different kinds of rocks—fails to teach the central goal of science which is to construct models that can be used to explain phenomena. Second, it fails to address the issue of generalization—do all materials exist in solid and liquid form? Do very small things sink (or float)? Third, it does not foster connections between concepts—do melting and evaporation have anything in common with transforming a rock into sand or lava solidifying? What causes objects to sink or float, and when they sink, to raise the level of the liquid? Perhaps most crucially, privileging topics over concepts does not give enough consideration to whether core concepts and principles are made sufficiently transparent through the selected phenomena. For example, water cycle is a common curriculum topic in the elementary grades, but is addressed at a regional or global scale, a scale too large for young children to build the case that water vapor still exists because the weight of the observed system has not changed. More generally, the topics approach downplays, the conceptual complexity "interesting phenomena" represent for children.

Interest and motivation to learn is of course important, as is linking school teaching to everyday phenomena, and important world issues such as global warming and energy conservation. We believe that a concept-centered approach need not be boring nor divorced from real world phenomena. In the LPM approach topics are not ignored but rather are chosen to be in the service of the core concepts; they need to provide a coherent storyline within which to situate conceptual development and a way to design teaching units on the basis of children's spontaneous interpretations and with the goal of transforming their interpretations, rather than simply challenging or ignoring them. For example, our fourth grade curriculum is placed within the context of earth materials, as preferred by the schools in which we worked. One of our end goals is that students be able to distinguish between kind of material and state (this is solid iron, this is liquid iron), a distinction that eludes a significant number of third graders. However scientific terms like "rock" and "sand" are semantically complex as they refer to materials composed of certain atoms, in a certain grain size, playing right into students' confusion. Consequently, this curricular unit makes the distinction a focus of the earth material lessons (instead of simply ignoring these conceptual complexities). We consider the water cycle an important topic but introduce it in fifth grade in the context of a tabletop system in which evaporation, condensation, and conservation of weight can be observed. By then the ground for understanding evaporation and condensation has been laid by studying less challenging transformations first, and students have developed concepts of weight and volume and beliefs about their conservation that allow them to make sense of the gaseous state.

Although many existing curricula do take a multi-year approach, the focus is commonly on topic sequences (with all the limitations of a topics approach cited above) not systematically building understanding of core concepts. (See Kesidou & Roseman, 2002, for analyses of major commercial science textbooks series, which criticizes them on this score). Further, many central "topics" relevant to building macroscopic understandings of matter (e.g., units on developing weight and volume measurement or even an understanding of density) are currently addressed as within the math curriculum rather than the science curriculum. Needless to say, the way they are taught there typically does not stress their relation to concept building, but rather their relevance to the development of particular mathematical skills.

Another approach described as “spiraling curricula” does focus on developing concepts over a multi-year span of time. But at present, those curricula generally lack the rigorous conceptual analyses of what mastery of those concepts entails and the research basis that inform current learning progressions. A focus on concepts requires a rigorous analysis of the complex (inter-related) network of which they are a part, including its underlying epistemological and ontological foundations, coupled with an understanding of the learning mechanisms which can be used to foster meaningful reconceptualizations that are clearly assessable. It was the conclusion of a recent expert panel that: “Spiraling curricula do focus on the mastery of concepts over time, but they may lack a clear pattern of development, are seldom based on strong empirical foundations, and typically lack the validation evidence characterizing progressions.” (Corcoran, Mosher, & Rogat, 2009, p. 39).

Reconceptualizing Learning Goals: Anchors & Steppingstones

Mohan, Chen & Anderson (in press) have introduced the labels “lower anchor” to refer to the state of knowledge at the beginning of a LP and “upper anchor” to refer to its end point. It is important to identify intermediate states of knowledge which can become the targets for curricula at different grade ranges that will allow students to bridge successfully between the two anchors. We call those intermediate states “stepping stones.”

Many aspects of the lower anchor for the Inquiry curriculum have been established by cognitive developmental researchers (and confirmed by our pre-interviews). As mentioned in the “What is LPM?” Section our assumption is that many aspects of these conceptions are universal. In the lower anchor, liquids and solids are seen as similar in the sense that they can be seen, touched and held, but gases are not; weight is reliably assessed by hefting; the conservation of material identity across transformations and the distinction between material kind and state are sporadic and context-dependent; and weight is not conserved across transformations.

Establishing appropriate stepping stones may be more problematic, especially in an elementary school curriculum. If the curriculum is aimed at high school students, the target is the upper anchor (an “edited” version of) the expert theory (AMT in our case). But if the curriculum targets lower grades, there are many options for defining stepping stones.

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. We hypothesize that some states of the knowledge network along LPM qualify as stepping stones in that they are sets of concepts, beliefs, principles, models, numerical & mathematical understandings, and representational tools that provide students with coherent interpretations of a broad range of phenomena, while allowing to move forward toward AMT with further instruction. When LPM reaches a stepping stone, the network has undergone significant reconceptualization, has reached a new state of equilibrium and is *conceptually* closer to AMT than the lower anchor.

Thus LPM gives curriculum developers the means to set stepping stones for curriculum interventions by asking, given the grade range and the time frame of this curricular intervention, what kind of stepping stone should we aim for? I.e., what coherent subset of concepts and principles, representational tools, and epistemological points should we focus on, that will put students in the best position to learn productively from the next curriculum they will be exposed to?

Deciding on the basic content of the third grade and fourth grade curricula was rather straightforward because weight, volume and material have to be in place before conservation of mass, identity of material, weight and volume can make sense; and those need to be introduced in the context of solids and liquids, which are familiar to children and form an ontological category, before they are applied to gases, which, initially, are not part of that ontological category.

The fifth grade curriculum found us at a crossroad: given a limited number of lessons, we decided we could either aim for: (a) a stepping stone organized around an ontological reconceptualization of the concept matter—material objects include gases; weight and volume are inherent properties of matter; amount of matter and weight are conserved across phase changes; or (b) one organized around density, quantifying the notion of heavy for size developed in the fourth grade and developing new representational tools.

At the end of fourth grade, students have advanced their understanding of material, weight, and volume. They are now familiar with the additivity of weight, the belief that cutting a chunk of material repeatedly will never make the pieces disappear, and that any piece of material however small has weight. Their understanding of volume has become more stable. More now understand that "volume" refers to occupied 3D space and can be measured with cc cubes, or by reading the level in a graduated cylinder; that a solid sinking in liquid makes the level rise not according to its weight, but according to the volume it occupies. They are more likely to know that the identity of material is maintained when it is ground into powder; that grinding a solid does not change its weight, nor the volume it occupies; that, at equal size, objects made of different materials have different weights.

Thus, students are (potentially) ready, conceptually, to tackle density: objects made of certain materials are heavier for their size (volume) than objects made of other materials; leading to: some materials are denser than others. Epistemologically, dot models (Smith, Snir & Grosslight, 1992) could be used to combine teaching about modeling with illustrating that matter is "packed more tightly" in denser materials and the concept of mass. In addition, one could extend children's work with weight and volume lines, to develop their understandings of coordinate graphical representations. (See Lehrer, Schauble, Strom, & Pligge, (2001) for a detailed description of how they developed elementary school children's understanding of density using coordinate graph representations, by first modeling similarity of geometric form.) A unit on sinking and floating might be meaningful at this point. By the end this version of the fifth grade curriculum, the stepping stone would be a solid understanding, at the macroscopic level, of weight, volume, material, mass, and density, and their interrelations, consistent with the expert view.

Alternatively, we could work to develop the understanding that matter exists in three states; that some materials melt and freeze; and evaporate and condense; and that some materials dissolve in liquids. By the end of fourth grade, students are (potentially) ready to consider these transformations of matter, and to discover which properties of matter stays the same (weight, amount of stuff, material identity) and which don't. We could make the conservation of matter a central theme and even introduce a basic particulate model of matter (e.g., a model that assumes matter consists of different kinds of discretely spaced particles that have characteristic weights, held together by bonds, and in motion). Introducing a particulate model of matter at this juncture made sense because we believe it is the only way to truly explain melting, freezing, evaporating, condensing, and dissolving, thus fostering an epistemological understanding of modeling. It also allows a deeper understanding of "made of" and of why objects made of different materials differ in heaviness for size. Therefore, it is (potentially) a stepping stone not only to the atomic-molecular but to density.

We decided to take the latter approach for several reasons. Foremost among our reasons was that we thought it would be not only the most immediately accessible to students but also the stepping stone with the most pay-off or "legs" from a scientific perspective. Coming to view matter as fundamentally particulate, gases as matter, and mass as conserved has extremely wide ranging implications and therefore begins to introduce students to a productive new framework for thinking about matter. Additional bonuses were that the phenomena this would allow us to explore with students might be "newer", more inherently surprising and interesting to students, and more in line with some of the existing expectations of their science curriculum. We thought such a model would also have pay-off in helping students develop packing schemes that are one route for understanding some aspects of density.

We are currently wrestling with some deep issues as we work to develop the fifth grade curriculum that pursues this approach. A central issue is exactly what set of elements to include in a particulate model and how to introduce them in a way that helps students understand deeper epistemological issues about models, including their tentative revisable nature and their use as tools of inquiry.

Contrasting the Stepping Stones Approach to Other Approaches

The stepping stone approach can be contrasted to the more traditional top-down approach, informed more narrowly and exclusively by the expert theory and by a logical analysis of the content domain, as well as an approach based on interchangeable modules, both insufficiently guided by reconceptualizations. Too often, the expert theory is broken down into its different components, 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. In particular, these approaches under emphasize the inherent links between the development of mathematical and epistemological knowledge and content knowledge.

Second, some concepts or relations between concepts may not be (sufficiently) problematized, nor the priority of one concept relative to another recognized. For example in the expert theory, the relation between weight and matter is seen as problematic only in that students have difficulty differentiating weight from mass; ironically, this ignores a more fundamental problem—that not all things considered material have weight (on earth). Thus, evidence that air is material or that amount of matter is conserved during phase change is based on weight demonstrations, missing the mark. This is undoubtedly related to science educators being opposed to teaching that weight is an inherent property of matter because this is not "true." In contrast, we believe this is a very good example of a stepping stone element—an "incomplete truth" if you will, that is central to a reconceptualization of weight which is itself central to progressing toward the expert theory.

Similarly, the principle "matter exists in three states, solid, liquid, and gas" may be 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.

Fourth, an expert's theory approach will often misjudge the appropriate grade range in which to introduce different concepts or practices. For example, measurement is taken for granted in the expert theory and it is easy to believe that learning to measure is learning simple procedures (e.g., using a tape measure or a scale) and a collection of formulas. On the other hand, models are central to expert theories but rarely included in elementary and middle school curricula because, according to Piaget, they require logico-mathematical operations that do not develop until adolescence. In contrast, LP approaches appreciate the interdependence among concepts, practices, and meta-knowledge in knowledge building; they also rest on the new research base in cognitive development that recognizes the ability of young children to engage in a wide range of practices right from the start (National Research Council, 2007). Therefore, stepping stones link epistemology to content knowledge, and teaches about both interactively.

Fostering Reconceptualization: Levers and Linchpins

Two theoretical constructs—**lever concepts and linchpins**—help us select and order the content of our curriculum that are likely to foster reconceptualization. **Lever concepts** are core concepts that are already present in the lower anchor, but need reconceptualization; i.e., important components of the later concepts are present in the earlier ones but they also differ from their upper anchor counterparts in fundamental ways. They are **salient** in students' everyday thinking, and **densely connected** to other ideas, so they offer many **points of contact** with instructional material and therefore multiple sources for conceptual change. Thus they are the concepts most amenable to initial restructuring and ontological change. Once a lever concept has been partially restructured, it can be involved in restructuring other concepts, via *content relations* (e.g., weight can "help material along) or in constructing concepts that do not exist in the lower anchor (e.g., density), propelling students' knowledge network forward. In other words, lever concepts provide the "most bang for the buck " In the Inquiry Project, we have identified **weight, size,** and **material** as lever concepts that are central to the (later) development of other related concepts: **volume, density, and matter**

Because lever concepts and words referring to them already exist in the lower anchor, they provide meaningful entry points for all students. For example, one entry point for weight is that hefting "measures" weight. Presenting objects made of different materials (such as the density cubes, discussed earlier) is an entry point for discussing the properties of objects and materials. Thus it makes sense to base the early parts of the curriculum on lever concepts. In addition, because lever concepts are richly connected with many other concepts, "moving" them toward the upper anchor contributes to moving other concepts along or constructing new ones. In contrast, non-lever concepts in the expert network (such as volume, density, and matter) are not yet distinct concepts for students in the lower anchor nor symbolized with individual words (although components of these concepts may be part of other precursor concepts). Leading with these ideas would not only involve leading with new vocabulary, but would also potentially destabilize the system rather than propel the system forward.

The richness of the lever concepts is a challenge as well as a resource: Moving from the lower anchor to the upper anchor concepts involves modifying many interrelated beliefs. A challenge for teaching is how to help student "break into" the new system of ideas that constitutes the upper anchor. Clearly, new relations cannot be introduced all at once; so careful choices need to be made about sequences and ordering. These choices have important consequences—some may destabilize the system while others propel it forward. Thus we argue that decisions about that sequence and ordering of classroom activities can't come from analysis of the expert system alone; it is critically important to consider the form and organization of ideas in the lower anchor.

Focusing initial explorations on concepts that are already present in the lower anchor does not mean that one works on concepts in isolation, completes work on one concept before moving to the next or refrains from introducing students to new ideas or forms of symbolization. Instead, one always is considering portions of several concepts (foregrounding some, backgrounding others), working on successive subconcepts, such as scale weight, each of which involves relations among parts of concepts, revisiting concepts and amplifying the subconcepts and contexts considered. Further, new forms of symbolization are critical to the reconceptualization of the lever concepts themselves. Significantly, these forms of symbolization which we call "linchpins," are not typically exploited or used in the traditional curriculum.

Linchpins complement lever concepts in the reconceptualization process; they are not themselves concepts; they are "organizers." They express **structural** aspects of concepts and/or relations between concepts in the upper anchor. At the same time, they are **tools that make reconceptualizations possible** because they also make (some) sense within the lower anchor and are sources of inferences and discoveries about the physical variable they represent. Without them, hands-on experiments and observations would enrich the knowledge network in the lower anchor, but not propel it forward toward the upper anchor. In the Inquiry Project, we identified two linchpins, the measure line (for weight and volume) and the compositional model of matter.

Dot models (Smith et al, 1992) are a third kind of linchpin relevant to LPM, but are not currently part of the Inquiry Curriculum.

All three are *models* that capture some important *structural aspects* of physical quantities. As in all models, physical entities are represented symbolically in linchpins; but, unlike most scientific models, linchpins do not represent the causal interactions among physical variables (as, for example, White & Frederiksen's (2000) models of force and motion and electricity do); instead, they express some important characteristics of the quantification of physical variables. All three can be expressed as *visual representations* and all three express the *quantificational structures* of the upper anchor concepts (e.g., extensivity of weight and volume; relation between sweetness, amount of sugar, and amount of water). Thus, by definition, they do not exist in the lower anchor. Linchpins are constituted, during classroom activities, from knowledge elements in different domains--not only the domain under study, matter, (or more broadly the domain of physical objects and phenomena) but also the numerical and mathematical domain, and possibly, via analogy use, other domains. Moreover, once mastered in the context of one variable (e.g., the weight measure line), they can be used to represent other physical variables which share the same quantification structure (e.g., the volume measure line). Thus linchpins "*hold ideas together"* within and across certain concepts. Within a concept (e.g.,weight) they make available several aspects of its quantification, and their relations (e.g., units of weight have to be equal; the weight of an object is the number of weight units that equals it; the weight of two objects together is the sum of the weights of the objects; if one keeps dividing a chunk of matter, its weight decreases but never goes to zero.)

To illustrate the role of lever concepts and linchpins in the development of a curriculum sequence, we will now focus on two lever concepts, weight and material, and two linchpins, the weight measure line and the compositional model of matter that play an important role in the Inquiry Project curriculum.

Weight is a Lever Concept

Weight is an important aspect of children's physical world. By the time they enter third grade, children have learned many relations between weight and other physical concepts, including size and material—big things are heavier than small things; steel things are heavier than plastic things. Many also believe that tiny things and Styrofoam pieces, of any size, weigh nothing at all because, for the large majority of third graders, hefting is privileged as a way to measure weight—how heavy an object is *is* how heavy it feels. For the same reason, changing the shape of an object, as in Piaget's famous ball and pancake experiment, changes its weight. Third graders do not have a concept of density; some may have a sense of "heavy for size"—steel things are heavier for their size than plastic things—but, for most students, steel is heavy in the same sense that big things are heavy. Weight in the lower anchor differs from scientific weight in another crucial respect—it is not an inherent property of matter: small things weigh nothing, spatial (shape) transformations can change weight; so do grinding and melting. Those characteristics are related to each other—e.g., not tying weight to "stuff" and measuring it by hefting both contribute to the belief that small things have no weight.

It would be wrong to think that learning about weight is simply combining new knowledge (e.g., about measuring weight with a balance scale) with the heft sense of weight. “Combining” suggests enriching existing knowledge. In the case of lever concepts, new knowledge is integrated into the lower anchor *network***.** Integrating new knowledge into the network implies and amounts to not only changing the very nature of the concept but also reorganizing the parts of the network relevant to the concept, e.g., its relations to other concepts, rather than simply enriching the concept with more elements. For example, simply adding “makes side of the balance scale go down” to “feels heavier when I heft” causes conflicts—a small piece of steel may feel heavier than a big piece of wood, but actually be lighter. Without further instruction, some students may simply ignore the conflict—the object that feels heavier *is* heavier and “I don’t know how a scale works;” others may try to explain why the “lighter” object makes the scale go down (e.g., by invoking size as affecting the scale as well). Clearly learning the steps involved in using a scale does not amount to getting closer to the upper anchor. Resolving productively the conflict between scale weight and felt weight requires reconceptualizing weight in a profound way, and a carefully designed sequence of activities.

Nevertheless, hefting and using the balance scale are two productive entry points, and the initial conflict between them can be put to good use. Using a pan balance scale to establish whether two things have the same weight, and if not, which is heavier, is intuitively obvious to third graders because objects push on other things as they push on children’s bodies. So are the ideas that two identical things are heavier than one and, more generally, that adding stuff to an object increases its weight (as long as the piece you add is big enough). In other words, third-graders have some sense of the extensivity of weight although it is importantly different from its scientific counterpart. First, it is (importantly) limited by their belief that very small things don’t weigh anything at all, and therefore that adding small amounts to something doesn’t change its weight. Second, weight is linked to size rather amount of matter. Third, theirs is a qualitative understanding—more stuff-more weight—not “twice as much matter, twice as heavy.” These aspects of the lower anchor knowledge are related to each other and centrally related to the ontological belief (a belief that grounds what they think weight is)—the weight of an object is how hard it pushes or pulls on one’s body. Achieving an understanding of the extensivity of weight, including its link to amount of material, and the nature of good measurement are two main goals of working with weight measure lines.

Tools for Reconceptualization of Weight: The Balance Scale and the Weight Measure Line

In this section, we start by analyzing how the weight measure line, the quantification of weight, and the concept of weight itself are related in the upper anchor (expert understanding). We then explain that using a balance scale and a weight measure line can be meaningfully interpreted by young children, although in a limited way, when weights are compared qualitatively; therefore those are useful starting activities. We go on detailing that students can then move to comparing weights quantitatively and how a series of measuring activities coordinated with representing weights on the measure line and using it to draw inferences can lead to reconceptualize weight as an extensive property of matter.

Weight Measure Line and Balance Scale in the Upper Anchor

The weight measure line, as used in the upper anchor, expresses the quantification of weight, i.e., that weight is an extensive property of matter—doubling the amount of matter doubles its weight; concatenating three identical objects results in an object with triple the weight. Weight is also gravitational force, so that the equality of the weights of two objects can be established with a balance scale. That is why the weight of an object (let us call it A) can be measured by establishing its equivalence to the weight of a set of identical objects (the weight of each of these objects is a weight unit) via a balance scale and counting the number of weight unit objects. The operation of physically concatenating a set of weight unit objects can be represented by numerical addition of 1's. Therefore, the weight of A can be represented by the cardinality of the sets of weight unit objects—i.e., by counting the weight unit objects. The weight of the object resulting from concatenating two amounts of matter, A and B, can be computed by adding the numbers representing the weight of A and the weight of B. And similarly the effect of removing an amount of matter from another one can be computed via subtraction.   Thus, the number line can be used as a model or visual representation of weight and of the weight transformations resulting from concatenating, dividing, or removing amounts of matter.

Elements that can be Recruited from Students' Lower Anchor to Construct, Use, and Learn from Using a Scale and a Weight Measure Line

We have argued above that heft and a qualitative understanding of the balance scale provided useful entry points for learning to measure weight, and therefore to start reconceptualizing it. Third graders also know about integers; have an implicit understanding of cardinality—the last count word represents the cardinality of a set, i.e., tells you "how many objects there are"—; know that, if you combine two sets of objects, you can compute how many there are by adding the numbers of objects in each set; and can represent integers on a number line.

All these pieces of knowledge in the lower anchor can be organized and **coordinated** by involving students in **measuring** weight using a pan balance, and **representing** their measurements on a weight line. The weight line can then be used to support **computations** and **inferences. Coordination and inferences are sources of genuinely new knowledge** about weight and of its **reconceptualization**.

Constructing a Weight Line: Linking Felt Weight and Scale Weight

Initially in the third grade Inquiry Curriculum, the weight line is an actual linear array of objects (density cubes) according to increasing felt weight. (Step 1 in Figure 1 below.) Uncertainties about some pairs of cubes motivate the use of a balance scale. Students readily relate the functioning of the scale to their own hefting, a similarity which helps establish the pan balance as a good means of comparing weight. As they realize that the balance scale is both more sensitive and more reliable than hefting their focus switches easily to arraying objects according to comparisons with the balance scale; the concept of weight, at this point, is enriched with "the scale hefts more accurately than I do." The weight line displays weights ordinally, without numbers. (Step 2 in Figure 1 below).

The next investigation ups the ante--children move from the question of which cube is heavier to the question *how much heavier*. This question cannot be answered without quantifying weight.

More problematically, the question itself can only have a relatively vague or metaphorical meaning until weight is measured in terms of units. The lower anchor concept of weight lends itself to qualitative comparisons only—A is heavier than B which is heavier than C. For “the weight of B is twice the weight of C” to be meaningful, weight has to be conceptualized as a ratio variable (i.e., weight units and weight = 0 must have meaning). Moreover for “the weight of B equals the weight of A and C combined” weight needs to be conceptualized as an extensive variable.

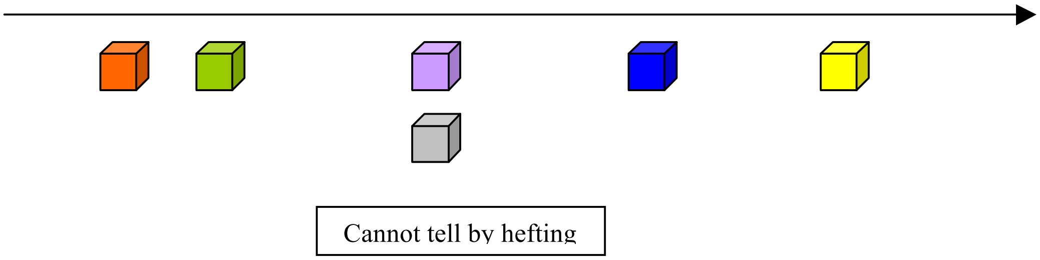
How can classroom activities revolving around a question students cannot fully grasp be productive? Using the balance scale and being able to refer to the weight measure line helps shape the meaning of the question.

Measuring Weights with Weight Units and Using the Weight Measure Line

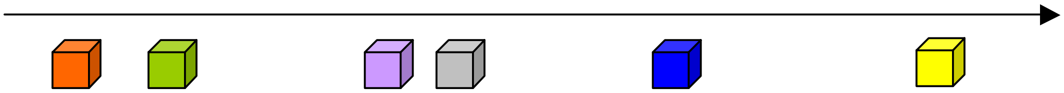
In a series of activities using the balance scale and non-standard units—plastic bears, paper clips, and washers—third grade students discover the need for a *uniform* and *shared* system of weight units (Step 3 in Figure 1 below). Standard units are then introduced, which students use to measure the weights of the density cubes. Students place the density cubes along the weight line, according to their weights in grams (Step 4 in Figure 1 below). They can now discuss the quesiton *How much heavier (or lighter) is one object than another?*

Figure 1. Using the weight measure line to represent qualitative and quantitative ordering of the weights of the density cubes.

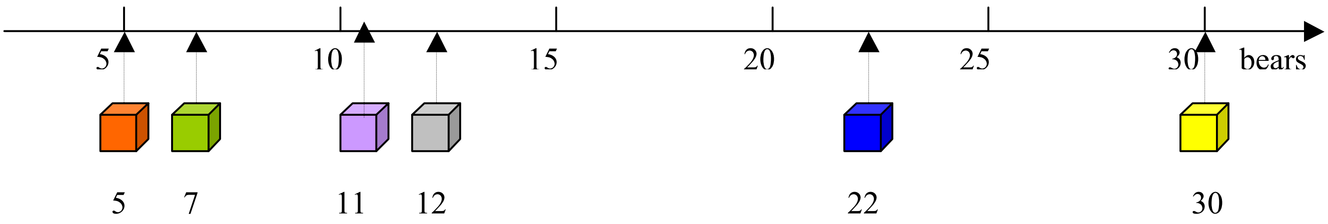
Step 1. Ordering by hefting



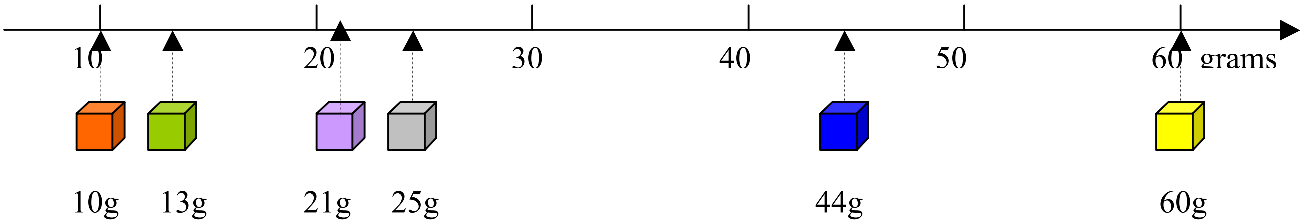
Step 2. Ordering by comparing objects with the balance scale



Step 3. Measuring weights with a balance scale and plastic bears



Step 4. Measuring weights with balance scale and standard units



What happened to the argument that one cannot make sense of this question without reconceptualizing weight? It still holds. However students can make progressive sense of the question and its answer by participating in a series of ordered and orchestrated activities in which they move back and forth between measuring weight with the balance scale and using the weight line. Going back and forth between the world of objects and the visual representation results in an increasing understanding of weight as quantifiable and extensive, and of the weight line as a weight measure line embodying those properties.

Measuring the weight of a density cube with a balance scale and non-standard units can be understood with the lower anchor concept. How many plastic bears have the same weight as the cube, i.e., how many bears does it take to balance the cube? are meaningful questions for a student who holds the lower anchor weight concept. The "weight" part of the question (making the weights equal) is qualitative. The answer—"7 bears"-- is quantitative but it is not weight that is quantified (yet), it is the number of bears with a weight equal to the weight of the cube.

Number of bears can be displayed on a *number line*, a process familiar to young students. But the line is already a *weight line* because it has been used to represent the qualitative ordering of the weight of the cubes. Without knowing it explicitly, students are *blending* (in Fauconnier and Turner's (2003) sense) a number line and the qualitative weight line, i.e., they are applying the properties of numbers (at first, of integers) to weight.

A first reconceptualization involves the weight line and language. The teacher shifts the emphasis from "How many bears have the same weight as the cube?" to "What is the *weight of the cube in bears*?" and then "What is the weight of the cube? "Seven bears." This shifts "bear" from being an object with a certain weight to being a weight unit. As the meaning of "bear" shifts, students are developing a sub-concept of weight around the belief that weight can be *measured with a balance scale;* it can be assigned *numbers*. This sub-concept is weight as an objective, quantifiable property. It is compatible with the rest of the lower anchor concept--the blue cube felt heavier than the green cube; it made the scale go down when they were placed in the balance pans, and now, its weight in bears is greater.

Once this first reconceptualization has taken place, using a balance scale to measure weight in *grams* is a meaningful activity. (Without being scaffolded by using non-standard units first and without the weight line, the same activity may have remained a routine with shallow meaning.)

Drawing Inferences from the Weight Measure Line

Students can start exploring new questions. Are there objects that are just one gram apart in weight? Can objects be less than a gram apart? How many? The fact that there are other weights "in between" any two weights on the measure line becomes more apparent as children imagine cubes made of other materials (clay, soap, stone, glass, brick, concrete), and speculate where their imaginary cubes might go on the line and why. These activities enrich the new sub-concept—objective quantifiable weight-- and the meaning of weight units. They also help develop the notion that weight is a continuous variable (an issue we will not develop in this paper).

The next question--How much weight would need to be added to the oak cube to have it be the same weight as the pine cube?—can be answered empirically, using the balance scale. Place the pine cube in one pan, the oak cube in the other pan and see how many grams need to be added to the pine cube to balance the scale. It can also be answered by using the weight line. How to do so is not obvious and is challenging for many students. The isomorphism between physical actions with cubes, grams and balance scale, and counting line segments and reading marks on the weight line gives the weight line its "measuring" meaning. In other words, students develop the implicit understanding that the conclusions one reaches by reasoning with the weight line are true of the real world. They learn to validate the weight line as a model of weight.

More generally, students will internalize the structure of the weight line as the quantificational structure of weight. One weight unit is represented by one line segment on the weight line. The weight of an object is represented by as many contiguous line segments as there are grams balancing the object on the scale. When one reads "the weight of this object is 15g" from the mark on the line, one is also taking in that it is the sum of 15 weight units.

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More Inferences from the Weight Measure Line and Discovery about the Relation of Weight and Material

As students become accustomed to thinking of weight along the weight line, interesting questions arise about smaller and smaller pieces of material. For instance, many students do not immediately understand that there can be values on the weight line between say, 3 and 4 grams, or more interestingly, between 0 and 1 gram. The visual representation of weight makes this idea graspable, especially if it is linked to the idea that a more sensitive scale would discriminate between these different weights.

Can one make pieces of stuff small enough that they stop weighing anything? Students break a 4g piece of Playdough in two, placing one of the pieces on the 2g mark, and keep going, toward the origin of the weight line. This leads to discussion, “Will you ever reach 0?” Do you think a tiny piece could weigh nothing at all?” The weight line is part of the argument. Representing 1g with a larger line segment allows them to keep dividing it further…The weight line also remains yoked to the real world—a very sensitive scale would detect a very small piece.

Many students conclude from these (and other) activities that indeed, any tiny piece must have weight.

Weight line discussions also help give meaning to the zero point. For example, we have found it is not initially obvious to students that weight lines start at 0. Some students think light objects weigh less than 0; further when students consider what happens with repeated division, some confuse repeated division with repeated subtraction and get to negative numbers. Part of the confusion is with students’ understanding of fractions and numbers. These weight line discussions are an important context for grounding meaning of fractions and operations of division. Further, if weight is tied with amount of matter, it motivates thinking that the smallest amount would be no matter which be nothing or zero.

Conclusions

The activities and discussions engendered by measuring weight with a pan balance scale and constructing and using weight measure lines (potentially) create a new core sub-concept— “scale weight,” consistent with the scientific concept. Weight has become objective and extensive, measured by a scale, linked to amount of stuff than the concept of weight in the lower anchor. These changes are interdependent and amount to a reconceptualization which includes an ontological shift—weight is now a property of the material an object is made of, not of the object per se. This core sub-concept, the availability of a scale (or of more sensitive ones), the link between dividing an amount of stuff and dividing a line segment on the weight measure line, embodied by placing each piece where it belongs on the weight line, support the idea that even tiny pieces would weigh something, as well as starting to discuss the difference between “feels like it weighs nothing” vs. “weighs nothing

By foregrounding different features of the weight measure line gradually, aspects of students’ initial weight concept can be both capitalized on and recast to give meaning to the different features of this new representational tool. In other words, a piece-by-piece approach allows students’ initial weight concept to enable the restructuring, not hinder it. Back-and-forth inference between the weight line and weight itself is the vehicle for the progressive transformations.

The weight line’s role in the restructuring of weight qualifies as linchpin for several reasons (a) it links felt weight and scale weight while privileging scale weight and (b) it links the elements of weight measurement to knowledge about number and counting, and to components of the weight concept, via a common visual structure. Some elements of a weight line are applicable to other concepts, among them volume. For example, measures of volume can also be displayed along a volume measure line that has zero point, fixed units that can be subdivided into fractional parts. Although there are many other issues specific to volume that need to be worked through in developing its measures, students are aided in the process by having some more general understandings of measure from their work with earlier quantities. Further, Cartesian graphs combine two measure lines in ways that visually display inter-relations among two measures.

This is not the end of weight reconceptualization—e.g., students still need to differentiate "heavy" from "heavy for size" and discover weight does not change during physical transformations However, the subconcept can enter in more powerful generalizations and explanations than the lower anchor concept (e.g., that weight does not change if an object changes shape and why it does not). These and others will make scale weight richer more salient (relative to heft) and make further reconceptualization possible.

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Material is a Lever Concept

Material also is present in the lower anchor as a precursor concept, not yet compatible with a scientific concept. Materials are an important aspect of the physical world for young children, as they affect their interactions with objects. Children are familiar with the appearances and behaviors of some materials—glass breaks, plastic does not; rubber things bounce; steel is "heavy;" wood burns, butter melts; ice is frozen water, trees are wood. But they do not know what general properties distinguish one material from another, or have generalizations about material as a category. Although most eight-year-olds know that when a wooden spoon is cut into chunks, it is not a spoon any more but the pieces are still wood, many believe that sawdust is not wood, and are not sure whether it would burn. They are more doubtful about material identity when less familiar materials are ground, especially if color changes, and even less sure when a solid melts. Thus material is not yet an ontological category distinct from state of matter.

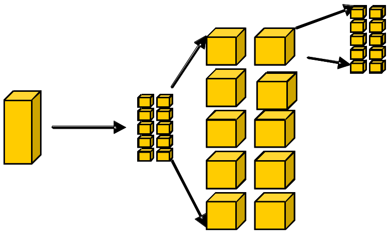
As for weight, constructing a new concept of material involves changing a significant part of the knowledge network: differentiating kind of material vs. state of matter, establishing the relevance of some properties and the irrelevance of others in identifying materials (e.g., density and being magnetic vs. color), developing a new meaning for "made of," by envisioning any little piece of chunk of X as X; conserving material identity across phase change, etc. As for weight, the changes are interrelated, support each other, and result in a new ontological category— material, as a specific form of matter distinguishes from other forms of matter by specific properties that can exist, in most cases, in more than one state.

Like weight, material evolves from perceptually based to being more closely and inherently tied to the "stuff" objects are made of as it becomes a form in which matter exists rather than a collection of perceptual properties. As with weight, a subconcept consistent with the scientific notion of material is constructed, which then "grows" because it supports widely applicable explanations and generalizations: once material is inherently linked to matter and distanced from perceptual properties, it is easier to believe that melted X is still X even if it does not look like X in solid form.

One can see that those different aspects of the reconceptualization of material are not independent of each other; for example, understanding the distinction between the identity of a material and its physical state is closely linked to understanding "made of" as "composed of." In addition, aspects of the reconceptualization of material are related to aspects of reconceptualizing weight as students relate weight to amount of material, differentiate weight and density, and know that density is a distinguishing property of materials.

Tool for Reconceptualization of Material: Compositional Model of Material

To apply a compositional model to a chunk of material involves mentally decomposing it into pieces; each piece maintains its identity while, as a group, they keep constituting the original whole. Like the weight line, this model also involves explicit symbolization, although it works with mental symbols and images rather than physical inscriptions.



Students can start cutting a chunk physically, then turn the operation into a thought experiment. The picture represents mentally enlarging the chunk in order to cut each piece into smaller and smaller pieces.

We hypothesize that a compositional model contributes to enriching the belief in conservation of amount of material during shape change, cutting and grinding. Most elementary school children say that changing the shape of an object (Piaget's ball and pancake transformation) does not change "how much clay there is" because "you did not add or take away any." The compositional model supports, deepens, and extends this judgment by providing an explanation—the ball can be thought of as made of pieces of clay, the pieces are simply rearranged into a pancake; their number does not change therefore amount of clay does not change either.

Cutting a chunk of material into pieces, including grinding it, is "the compositional model in action"—the pieces still constitute the whole. Thinking in terms of the compositional model should help students realize that the powder has the same amount of material as the original chunk, although it appears very different.

The compositional model is particularly useful as a thought experiment when students are investigating cutting a piece of material again, and again, and again; will pieces get so small that they will eventually disappear? Many elementary school children think so. But when asked to keep the whole chunk in mind-if the pieces all disappear, it is like making the chunk disappear by cutting it—they might change their mind.

The compositional model should also support the conservation of *material identity.* Some early elementary school students know that powders are the "same stuff" as the chunk they came from, but others say it is not the same material because it looks different (e.g., the powder is a different color.) Mentally grinding the material does not change its appearance; it may offer support for believing that the powder is the same material as the chunk.

We hypothesize that the compositional model can contribute to the restructuring of the concept of weight as well—the sum of the weights of the pieces has to be the weight of the chunk since all they do is superimpose a "grid" on the chunk. This supports the extensivity of weight, and its quantification. It also supports adopting the belief that all matter has weight—however small the pieces children envision, they still make up the whole; therefore even the tiniest piece has weight.

The same inferences can be drawn about the volume of a chunk of material. Through the lens of a compositional model, volume and weight become quantifiable, extensive, and inherent properties of pieces of any material of any size.

A compositional model can also serve as a stepping stone to schemas of the packedness of particles that can be used for thinking about a broader range of phenomena (e.g., varying concentrations in mixtures, mass being conserved while volume changes when an object is heated).

To summarize, the compositional is a linchpin for multiple reasons. First, it can be constructed from three different pieces of knowledge in the lower anchor although it is not contained in the lower anchor—(a) mentally dividing a chunk is like physically cutting it; (b) object permanence (pieces of stuff continue to exist when they are spatially displaced); and (c) number conservation (the number of pieces stays the same when they are spatially rearranged). Second, it embodies the quantification of amount of matter, weight, and volume. Third, it supports inferences which lead to new knowledge (tiny pieces of matter continue to exist, have weight and have volume). Finally, it "holds things together" in several ways—conservation and identity are tied to quantification; the model applies to amount of matter, volume, and weight; and it embodies the principle that volume and weight are intrinsic properties of matter.

How Novel are Lever Concepts and Linchpins?

Unfortunately, much of science education involves prematurely introducing new ideas and symbols without consideration of how they will be understood by students. Our approach is committed to thinking through sequences that work to move the network forward while preserving intelligibility to students. Lever concepts are key to this enterprise as they are present in both the lower and upper anchor. Because they exist in the lower anchor it is easy to assume that they are not problematic and to overlook them (how problematic could weight be, if toddlers use the word "heavy"?) and yet they are profoundly different from their scientific counterparts and need extensive reconceptualization. Traditional curricula often relegate weight to the math curriculum until it needs differentiating from mass. Similarly, they jump from material as a topic for kindergarten, to the distinction between element, substance and compound in chemistry, not taking into account that exploring materials in kindergarten is only a useful first step; elementary school students need a chance to build an understanding of the relation between material and weight, understand the meaning of “made of;” and be given means to understand that material identity does not change during phase change.

At the same time, lever concepts provide the basis on which to build the scientific concept, and help reorganize other concepts. Therefore it is important to give them primacy in the curriculum. Too often, curricula focus exclusively on concepts that are more obviously problematic, e.g., density, without realizing those concepts are constructed on a foundation of lever concepts and might be less problematic if lever concepts were privileged.

Linchpins are key to the process of reconceptualization and yet either they are absent from the curricula or their role in reconceptualization is not acknowledged. The reason that the compositional model is ignored is probably that it captures aspects of the concepts of weight, volume, and amount of material, and their relations, which are not considered problematic. Measure lines are part of the curriculum but not as agents of reconceptualization.

The importance of linchpins in the Inquiry Curriculum is consistent with the prominence of measuring, symbolizing, and modeling in other innovative curricula **(**Acher & Arca, 2006; Carraher, Schliemann, Brizuela & Earnest, 2006; Lehrer and Schauble, 2005; Schliemann, Carraher, & Cadde, unpublished manuscript). Linchpins make salient that conceptual change results from the co-construction of representations and concepts through successive mappings between the two (Acher & Arca, 2006; Lehrer & Pritchard, 2002; Roth, 2003) Moreover linchpins integrate science and mathematics, instead of confining measurement to the math curriculum where it remains formulaic, not being given the conceptual foundation it needs, nor a chance to contribute to conceptual change.

Conclusion

In sum, this paper uses examples from the Inquiry Project to illustrate four aspects we believe are inherent to a learning progressions approach to curriculum development: organizing curriculum around core concepts rather than topics, revisiting core concepts across grades, establishing learning goals in terms of anchors and stepping stones, and using lever concepts and linchpins to foster reconceptualization. We have developed the theoretical constructs of stepping stones, lever concepts, and linchpins.

The validity of those constructs is ultimately an empirical issue: how reliably they can be established for different curricula in different domains? How successful are the curricula on which they are based? The findings from our longitudinal study will bear on whether the stepping stone, linchpins and levers we chose were useful. Were we able to produce more coherent understandings in our Treatment than Control group? But other longitudinal studies, based on other curricula will also be needed to compare the merits other choices.

We are engaged in a two-way process: implementing and testing a curriculum based on LPM is a major process in revising not just the curriculum itself, but the content of LPM, the theoretical constructs that structure LPM, and more generally the construct of LP.

References

Acher, A., & Arca, M. (2006). Children's representations in modeling scientific knowledge construction. In C. Andersen, M. N. Scheuer, M. P. Perez Echeveerria, & E. Teubal (Eds.), *Representational systems and practices as learning tools in different fields of knowledge*. Sense Publishers

Carey, S. (2008). *The origin of concepts*. Oxford, UK: Oxford University Press.

Carraher, D., Schliemann, A.D., Brizuela, B., & Earnest, D. (2006). Arithmetic and Algebra in early Mathematics Education. Journal for Research in Mathematics Education, Vol. 37(2), pp. 87-115.

Corcoran, T., Mosher, F.A., & Rogat, A. (2009). Learning Progressions in Science. A Evidence Based Approach to Reform. Research Report # RR-63. Center on Continuous Instructional Improvement. Teachers College–Columbia University.

Fauconnier, G. & Turner, M. (2003). *The Way We Think: Conceptual Blending and the Mind's Hidden Complexities*. Basic Books.

Kesidou, S., and Roseman, J.E. (2002). How well do middle school science programs measure up? Findings from Project 2061's curriculum review. *Journal of Research in Science Teaching, 39*(6), 522-549.

Kuhn, T.S. (1962). *The Structure of Scientific Revolutions.* University of Chicago Press.

Lehrer, R., & Pritchard, C. (2002). Symbolizing space into being. In K. Gravemeijer, R. Lehrer, B. van Oers, & L. Verschaffel (Eds.), *Symbolization, modeling and tool use in mathematics education***,** pp. 59-86. Dordrecht, Netherlands: Kluwer Academic Press.

Lehrer, R., Schauble, L., Strom, D., & Pligge, M. (2001). Similarity of form and substance: Modeling material kind. In S. Carver & D. Klahr (Eds.), *Cognition and instruction: Twenty-five years of progress*, pp. 39-74. Mahwah, NJ: Erlbaum.

Mohan, L., Chen, J., & Anderson, C. (in press) Developing a Multi-year Learning Progression for Carbon Cycling in socio-Ecological Systems. Manuscript accepted for publication in *Journal of Research in Science Teaching.*

National Research Council (2007). *Taking science to school: Learning and teaching science in grades K-8.* Washington, D.C.: National Academies Press.

Pinker, S. (2007). *The Stuff of Thought: Language as a Window into Human Nature.* Viking Press.

Roth, W-M. (2003). *Toward an Anthropology of Graphing.* Dordrecht, The Netherlands: Kluwer Academic Publishers.

Schliemann, A.D., Carraher, D.W., & Cadde, M.C. Learning about intervals in the Cartesian space. Unpublished manuscript.

Smith, C.L, Snir, J., & Grosslight, L. (1992). Using conceptual models to facilitate conceptual change: The case of weight/density differentiation. *Cognition and Instruction*, *9* (3), 221-83.

Smith, C.L., Wiser, M., Anderson, C.W. & Krajcik, J. (2006). Implications of research on children's learning for standards and assessment: A proposed learning progression for matter and atomic-molecular theory. *Measurement: Interdisciplinary Research and Perspectives*, 14 (1-2), 1-98.

Spelke, E.S. (2000). Core knowledge. American Psychologist, 55, 1233–1243.

White, B., & Frederiksen, J. (2000). Technological tools and instructional approaches for making scientific inquiry accessible to all. In M. Jacobson & R. Kozma (Eds.), *Innovations in science and Mathematics education. Advanced designs for technologies of learning*, pp. 321-60. Mahwah, NJ: LEA.

Wiser, M. & Smith, C. L. (2008). Teaching about matter in grades K-8: When should the atomic-molecular theory be introduced? In S. Vosniadou (Ed.), *International handbook of research on conceptual change.* Hillsdale, N.J. Erlbaum.