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# Chapter 20

# Knowledge Acquisition: Enrichment or Conceptual Change?

*Susan Carey*

There is a broad consensus that learning requires the support of innate representations (cf. Carey and Gelman 1991, Hirschfeld and Gelman 1994, Johnson and Morton 1992, but see also Elman et al. 1996). Further, recent data allow the characterization of some of the innate representations that guide cognitive development (see especially Gallistel et al. 1991, Marler 1991, and Spelke 1991). Spelke (1991) defends a stronger thesis: The initial representations of physical objects that guide *infants'* object perception and *infants'* reasoning about objects remain the core of the *adult* conception of objects. Spelke's thesis is stronger because the existence of innate representations need not preclude subsequent change or replacement of these beginning points of development. Her argument involves demonstrating that infants young as 2 1/2 to 4 months expect objects to move on continuous paths and that they know that one object cannot pass through another. She concludes by making a good case that these principles (spatiotemporal continuity and solidity) are central to the adult conception of objects as well. In the case of the concept of a physical object, cognitive development consists of enrichment of our very early concept, not the radical change Piaget posited.

I do not (at least not yet) challenge Spelke's claim concerning the continuity over human development of our conception of physical objects. However, Spelke implies that the history of the concept of an object is typical of all concepts that are part of intuitive adult physical reasoning. Further, she states that in at least one crucial respect, the acquisition of commonsense physical knowledge differs from the acquisition of scientific knowledge: The development of *scientific* knowledge involves radical conceptual change. Intuitive conceptions, in contrast, are constrained by innate principles that determine the entities of the mentally represented world, thus determining the entities about which we learn, leading to entrenchment of the initial concepts and principles. She suggest that going beyond these initial concepts requires the metaconceptually aware theory building of mature scientists. To the degree that Spelke is correct, the scope for a constructivist genetic epistemology as envisioned by Piaget is correspondly small; normal cognitive development would involve minimal conceptual change and no major conceptual reorganizations.

Spelke's claim is implausible, on the widely held assumption of the continuity of science with commonsense explanation (e.g., Nersessian 1992). Of course, Spelke rejects the continuity assumption. In this chapter, I deny Spelke's conjecture that ordinary, intuitive, cognitive development consists only of enrichment of innate structural principles. The alternative that I favor is that conceptual change occurs during normal cognitive growth. Let me begin by settling some terminological matters. By *concept*, *belief*, and *theory*, I mean mentally represented structures. Concepts are units of mental representation roughly the grain of single lexical items, such as *object, matter,* and *weight.* Beliefs are mentally represented propositions taken by the believer to be true, such as *Air is not made of matter.* Concepts are the constituents of beliefs; that is, propositions are represented by structures of concepts. Theories are complex mental structures consisting of a mentally represented domain of phenomena and explanatory principle that account for them.

The debate between the enrichment and conceptual change views of cognitive development touches some of the deepest problems of developmental psychology. One such problem is the origin of human concepts. Theories of the origin of concepts are organized around two poles: the extreme nativist view that all concepts of the grain of single lexical items are innate (see Fodor 1975 for an argument in favor of this position) and the empiricist view that new concepts arise by combination from innate primitives (see Jackendoff 1989 for a modern statement of this position). As regards knowledge acquisition, both views are enrichment views, although the type of enrichment envisioned differs. On Fodor's view, knowledge acquisition consists of addition and changes of beliefs; on Jackendoff's, new concepts may also come into being, but these are defined in terms of innate primitives. Like Piaget's constructivism, the conceptual change position stakes out a third possibility, that new concepts may arise that are not definable in terms of concepts already held. Another problem touched by the debate concerns the origin of knowledge. Is knowledge acquisition merely a matter of belief revision? For example, when a child says that a piece of rice weighs nothing at all, is he or she merely expressing a false belief that he or she will eventually revise, or is the child expressing a true belief in terms of a concept of weight that differs from the adult's?

In keeping with current theorizing in cognitive psychology, I take concepts to be structured mental representations (see Smith 1989 for a review). A theory of human concepts must explain many things, including concepts' referential and inferential roles. Concepts may differ along many dimensions, and no doubt there are many degrees of conceptual difference within each dimension. Some examples of how concepts change in the course of knowledge acquisition follow:

1. What is periphery becomes core, and vice-versa (see Kitcher 1988). For example, what is originally seen to be the most fundamental property of an entity is realized to follow from even more fundamental properties. Example: in understanding reproduction, the child comes to see that being small and helpless are derivative properties of babies, rather than the essential properties (Carey 1985b, 1988).
2. Concepts are subsumed into newly created ontological categories or reassigned to new branches of the ontological hierarchy (see Thagard 1990). Example: Two classes of celestial bodies—stars and planets/moons—come to be conceptualized, with the sun and the earth as examples, respectively (Vosniadou and Brewer 1992).
3. Concepts are embedded in locally incommensurable theories. Example: the concepts of the phlogiston and oxygen theories of burning (Kuhn 1982).

According to Spelke, knowledge acquisition involving all three sorts of conceptual change contrasts with knowledge acquisition involving only enrichment. Enrichment consists in forming new beliefs stated over concepts already available. Enrichment:

New knowledge about entities is acquired, new beliefs represented. This knowledge then helps pick out entities in the world and provides structure to the known properties of the entities. Example: the child acquires the belief "unsupported objects fall" (Spelke 1991). This new belief influences decisions about object boundaries.

In this chapter, I explore the possibility of conceptual change of the most extreme sort.[1] I suggest that, in some cases, the child's physical concepts may be incommensurable with that of the adult's, in Kuhn's (1982) sense of local incommensurability. It is to the notion of local incommensurability that I now turn.[2]

## 1. *Local Incommensurability*

### *Mismatch of Referential Potential*

A good place to start is with Philip Kitcher's analysis of local incommensurability (Kitcher 1988). Kitcher outlined (and endorsed) Kuhn's thesis that there are episodes in the history of science at the beginnings and ends of which practitioners of the same field of endeavor speak languages that are not mutually translatable. That is, the beliefs, laws, and explanations that are statable in the terminology at the beginning, in language 1 (L1), cannot be expressed in the terminology at the end, in language 2 (L2). As he explicated Kuhn's thesis, Kitcher focused on the referential potential of terms. He pointed out that there are multiple methods for fixing the reference of any given term: definitions, descriptions, and theory-relative similarity to particular exemplars. Each theory presupposes that for each term, its multiple methods of reference fixing pick out a single referent. Incommensurability arises when an L1 set of methods of reference fixing for some term is seen by L2 to pick out two or more distinct entities. In the most extreme cases, the perspective of L2 dictates that some of L1's methods fail to provide any referent for the term at all, whereas others provide different referents from each other. For example, the definition of "phlogiston" as "the principle given off during combustion" fails, in our view, to provide any referent for "phlogiston" at all. However, as Kitcher pointed out, in other uses of "phlogiston," where reference is fixed by the description of the production of some chemical, it is perfectly possible for us to understand what chemicals are being talked about. In various descriptions of how to produce "dephlogisticated air," the referent of the phrase can be identified as either oxygen or oxygen-enriched air.

Kitcher produced a hypothetical conversation between Priestley and Cavendish designed to show that even contemporaries who speak incommensurable languages can communicate. Kitcher argued that communication is possible between two parties, if one can figure out what the other is referring to and if the two share *some* language. Even in cases of language change between L1 and L2, the methods of reference fixing for many terms that appear in both languages remain entirely constant. Further, even for the terms for which there is mismatch, there is still some overlap, so that in many

1. Spelke points out that Piaget's claim for changes in the conception of objects during infancy are more extreme than any of the four enumerated here. Piaget denies the infant any *conception* of objects at all, granting only ephemeral sensory experiences. I endorse Spelke's counterarguments to Piaget's position; see also Leslie (1988) and Mandler (1988).

2. My explication of local incommensurability closely follows Carey (1988) though I work through different examples here.

contexts the terms will refer to the same entities. Also, agreement on reference is possible because the two speakers can learn each others' language, including mastering the other's methods of reference fixing.

The problem with Kitcher's argument is that it identifies communication with agreement on the referents of terms. But communication requires more than agreement on referents; it requires agreement on what is said about the referents. The problem of incommensurability goes beyond mismatch of referential potential.

*Beyond Reference*

If speakers of putatively incommensurable languages can, in some circumstances, understand each other, and if we can, for analogous reason, understand texts written in a language that is putatively incommensurable with our own, why do we want to say that the two languages are incommensurable? In answering this question, Kuhn moved beyond the referential function of language. To figure out what a text is referring to is not the same as to provide a translation for the text. In a translation, we replace sentences in L1 with sentences in L2 that have the same meaning. Even if expressions in L1 can be replaced with coreferential expression in L2, we are not guaranteed a translation. To use Frege's example, replacing "the morning star" with "the evening star" would preserve reference but would change the meaning of a text. In cases of incommensurability, this process will typically replace an L1 term with one L2 term in some contexts and other L2 terms in other contexts. But it matter to the meaning of the L1 text that a single L1 term was used. For example, it mattered to Priestley that all of the cases of "dephlogisticated" entities were so designated; his language expressed a theory in which all dephlogisticated substances shared an essential property that explained derivative properties. The process of replacing some uses of "dephlogisticated air" with "oxygen," others with "oxygen-enriched," and still others with other phrases, yields what Kuhn called a disjointed text. One can see no reason that these sentences are juxtaposed. A good translation not only preserves reference; a text makes sense in L1, and a good translation of it into L2 will make sense in L2.

That the history of science is possible is often offered as prima facie refutation of the doctrine of incommensurability. If earlier theories are expressed languages that are incommensurable with our own, the argument goes, how can the historian understand those theories and describe them to us so that we understand them? Part of the answer to this challenge has already been sketched herein. Although parts of L1 and L2 are incommensurable, much stays the same, enabling speakers of the two language to figure out what the other must be saying. What one does in this process is not *translation*, but rather *interpretation* and *language learning*. Like the anthropologist, the historian of science interprets, and does not merely translate. Once the historian has learned L1, he or she can teach it to us, and then we can express the earlier theory as well.

On Kuhn's view, incommensurability arises because a language community learns a whole set of terms together, which together describe natural phenomena and express theories. Across different languages, these sets of terms can, and often do, cut up the world in incompatible ways. To continue with the phlogiston theory example, one reason that we cannot express claims about phlogiston in our language is that we do not share the phlogiston theory's concepts *principle* and *element*. The phlogiston theory's *element* encompassed many things we do not consider elements, and modern chemistry has no concept at all that corresponds to phlogiston theory's *principle*. But we cannot express the phlogiston theory's understanding of combustion, acids, airs, and so on, without using the concepts *principle*, *element*, and *phlogiston*, for these concepts are all interdefined. We cannot translate sentences containing "phlogiston" into pure 20th-century language, because when it comes to using words like "principle" and "element" we are forced to choose one of two options, neither of which leads to a real translation:

1. We use "principle" and "element" but provide a translator's gloss before the text. Rather than providing a translation, we are changing L2 for the purposes of rendering the text. The translator's gloss is the method for teaching L1 to the speakers of L2.
2. We replace each of these terms with different terms and phrases in different contexts, preserving reference but producing a disjointed text. Such a text is not a translation, because it does not make sense as a whole.

*Conceptual Differentiation*

As is clear from the preceding text, incommensurability involves change at the level of individual concepts in the transition from one language to the other. There are several types of conceptual change, including:

1. Differentiation, as in Galileo's drawing the distinction between *average velocity* and *instantaneous velocity*; see Kuhn (1997).
2. Coalescences, as when Galileo saw that Aristotle's distinction between *natural* and *violent* motion was a distinction without a difference and collapsed the two into a single notion.
3. Simple properties being reanalyzed as relations, as when Newton reanalyzed the concept *weight* as a relation between the earth and the object whose weight is in question.

Characterizing change at the level of individual concepts is no simple matter. We face problems both of analysis and evidence. To explore these problems, take just one type of conceptual change—conceptual differentiation. Developmental psychologists often appeal to differentiation when characterizing conceptual change, but not all cases in which distinctions that are undrawn come to be drawn imply incommensurability. The 2-year-old may not distinguish collies, German shephards, and poodles and therefore may have an undifferentiated concept of *dog* relative to adults, but the concept *dog* could well play roughly the same role in both the 2-year-old's and the adult's conceptual system. The cases of differentiation involving incommensurability are those in which the undifferentiated parent concept from L1 is incoherent from the point of view of L2.

Consider McKie and Heathcote's (1935) claim that before Black, *heat* and *temperature* were not differentiated. This would require that thermal theories before Black represented a single concept, fusing our concepts *heat* and *temperature*. Note that in the language of our current theories, there is no superordinate term that encompasses both of these meanings—indeed, any attempt to wrap heat and temperature together would produce a monster. Heat and temperature are two entirely different types of physical mangnitides; heat is an extensive quantity, whereas temperature is an intensive quantity. Extensive quantities, such as the amount of heat in a body (e.g., 1 cup of water), are additive—the total amount of heat in two cups of water is the sum of that in each. Intensive quantities are ratios and therefore not additive—if one cup of water at 80 °F is added to 1 cup at 100 °F, the resultant temperature is 90 °F, not 180 °F. Furthermore, *heat* and *temperature* are interdefined—for example, a calorie is the amount of heat required to raise the temperature of 1 gram of water 1 °C. Finally, the two play completely different roles in explaining physical phenomena such as that of heat flow. Every theory since Black includes a commitment to thermal equilibrium, which is the principle that temperature differences are the occasion of heat flow. This commitment cannot be expressed without distinct concepts of *heat* and *temperature*.

To make sense of McKie and Heathcote's claim, then, we must be able to conceive how it might be possible for there to be a single undifferentiated concept fusing *heat* and *temperature*, and we must understand what evidence would support the claim. Often, purely linguistic evidence is offered; L1 contains only one term, whereas L2 contains two. However, more than one representational state of affairs could underlie any case of undifferentiated language. Lack of differentiation between *heat* and *temperature* is surely representationally different from mere absence of the concept *heat*, even though languages expressing either set of thermal concepts might have only one word, e.g., "hot." A second representational state that might mimic nondifferentiation is the false belief that two quantities are perfectly correlated. For example, before Black's discoveries of specific and latent heat, scientist might have believed that adding a fixed amount of heat to a fixed quantity of matter always leads to the same increase in temperature. Such a belief could lead scientists to use one quantity as a rough and ready stand-in for the other, which might produce texts that would suggest that the two were undifferentiated.

The only way to distinguish these two alternative representational states of affairs (false belief in perfect correlation and absence of one or the other concept) from conceptual nondifferentiation is to analyze the roles that the concepts played in the theories in which they were embedded. Wiser and Carey (1983) analyzed the concept *heat* in the thermal theory of the 17th-century Academy of Florence, the first group to systematically study thermal phenomena. We found evidence supporting McKie and Heathcote's claim of nondifferentiation. The Academy's heat had both causal strength and qualitative intensity—that is, aspects of both modern *heat* and modern *temperature*. The "Experimenters" (their own self-designation) did not separately quantify heat and temperature and, unlike Black, did not seek to study the relations between the two. Furthermore, they *did* relate a single thermal variable, *degree of heat*, to mechanical phenomena. By analyzing contexts we now see *degree of heat* sometimes referred to temperature and sometimes to amount of heat. You may think of this thermal variable, as they did, as the *strength* of the heat and relate it to the magnitude of the physical effects of heat. The Experimenters used thermometers to measure degree of heat, but they did so by noting the rate of change of level in the thermometer, the interval of change, and only rarely the final level attained by the alcohol in their thermometers (which were not calibrated to fixed points such as the freezing and boiling points of water). That is, they did not quantify either temperature or amount of heat, and they certainly did not attempt to relate two distinct thermal variables. Finally, their theory provided a different account of heat exchange from that of the caloric theory of modern thermodynamics. The Experimenters did not formulate the principle of thermal equilibrium; their account needed no distinct concepts of heat and temperature. For all these reasons, we can be confident in ascribing a single undifferentiated concept that conflated *heat* and *temperature* to these 17th-century scientists. No such concept as the Experimenters' *degree of heat* plays any role in any theory after Black.

The Experimenters' concept, which is incoherent from our point of view, led them into contradictions that they recognized but could not resolve. For example, they noted that a chemical reaction contained in a metal box produced a degree of heat that was insufficient to melt paraffin, whereas putting a solid metal block of the same size on a fire induced a degree of heat in the block that was sufficient to melt paraffin. That is, the *latter* (the block) had a greater degree of heat. However, they also noted that if one put the box with the chemical reaction in ice water, it melted more ice than did the heated metal block, so the *former* (the box) had a greater degree of heat. Although they recognized this as a contradiction, they threw up their hands at it. They could not resolve it without differentiating temperature from amount of heat. The chemical reaction generates more heat but attains a lower temperature than does the block; the melting point of paraffin is a function of temperature, whereas how much ice melts is a function of amount of heat generated.

*Summary*

When we ask whether the language of children (L1) and the conceptual system it expresses (C1) might sometimes be incommensurable with the language (L2) and conceptual system (C2) of adults, where C1 and C2 encompass the same domain of nature, we are asking whether there is a set of concepts at the core of C1 that cannot be expressed in terms of C2, and vice-versa. We are asking whether L1 can be translated into L2 without a translator's gloss. Incommensurability arises when there are simultaneous differentiations or coalescences between C1 and C2, such that the undifferentiated concepts of C1 can no longer play any role in C2, and the coalesced concepts of C2 can play no role in C1.

## 2. *Five Reasons to Doubt Incommensurability between Children and Adults*

I have encountered five reasons to doubt that children's conceptual systems are incommensurable with adults':

1. Adults communicate with young children just fine.
2. Psychologists who study cognitive development depict children's conceptions in the adult language.
3. Where's the body? Granted, children cannot express all of the adult conceptual system in their language, but this is because L1 is a subset of L2, not because the two are incommensurable. Incommensurability requires that L2 not be able to express L1, as well as L1 not being able to express L2. Just as we cannot define "phlogiston" in our language, so holders of the phlogiston theory could not define "oxygen" in theirs. Where do children's conceptual systems provide any phenomena like those of the phlogiston theory? Where is a preschool child's "phlogiston" or "principle?"
4. There is no way incommensurability could arise (empiricist version). Children learn their language from the adult culture. How could children establish sets of terms that are interrelated differently from adult interrelations?

5. There is no way incommensurability could arise (nativist version). Intuitive conceptions are constrained by innate principles that determine the objects of cognition and that become entrenched in the course of further learning.

Those who offer one or more of the preceding objections share the intuition that although the young child's conceptual system may not be able to express all that the adult's can, the adult can express the child's ideas, that is, can translate the child's language into adult terms. Cognitive development, in this view, consists of enrichment of the child's conceptual system until it matches that of the adult.

*Adults and Young Children Communicate*

The answer to this objection should, by now, be familiar. Incommensurability does not require complete lack of communication. After all, the early oxygen theorists argued with the phlogiston theorists, who were often their colleagues or teachers. Locally incommensurable conceptual systems can share many terms that have the same meaning in both languages. This common ground can be used to fix referents for particular uses of nonshared terms, for example, a use of "dephlogisticated air" to refer to oxygen enriched air. Anyway, it is an empirical question just how well adults understand preschool children.

*Developmental Psychologists Must Express Children's Beliefs in the Adult Language: Otherwise, How Is the Study of Cognitive Development Possible?*

I discussed earlier how it is possible for the historian of science to express in today's language an earlier theory that was expressed in an incommensurable language. We understand the phlogiston theory, to the extent that we do, by *interpreting* the distinctive conceptual machinery and enriching our own language. To the extent that the child's language in incommensurable with the adult's, psychologists do not express the child's beliefs in the adult language. Rather, they interpret the child's language, learn it, and teach it to other adults. This is possible because of the considerable overlap between the two, enabling the psychologist, like the historian, to be interpreter and language learner.

*Where's the Body?*

As mentioned above, those who raise these objections believe that the child's concepts are a subset of the adult's; the child cannot express all adult concepts, but the adult can express all the child's. The body we seek, then, is a child's concept that cannot be expressed in the adult's language.

There are two cases of the subset relation that must be distinguished. If concept acquisition solely involves constructing new concepts out of existing ones, then the child's concepts will be a subset of the adult's, and no incommensurability will be involved. However, in some cases in which one conceptual system is a subset of another, *one-way* incommensurability obtains. For example, Newtonian mechanics is a subset of the physics of Maxwell. Maxwell recognized forces that Newton did not, but Maxwell did not reconceptualize mechanical phenomena. That is, Maxwell's physics could express Newton's. The reverse is not so. It is not possible to define electromagnetic concepts in terms of Newtonian concepts.

Although I certainly expect that there are cases of conceptual change in childhood that involve one-way incommensurability, full two-way incommensurability is the focus of the present analysis. In the most convincing cases of incommensurability from the history of science, some of the concepts of C1, such as "phlogiston" and "principle," have no descendents at all in C2. The body we seek is such a case in which the child's C1 contains concepts that are absent from the adult's C2—concepts that cannot be defined in C2. Note that *concepts* are the issue, not terms. Since children learn language from adults, we would not expect them to invent terms like "phlogiston" or "principle" that do not appear in the adult lexicon. However, two-way incommensurability does not require terms in L1 with no descendents in L2. Newtonian mechanics is incommensurable with Einsteinian mechanics, but Newton's system contains no bodies in this sense. Similarly, although the Florentine Experimenters' source-recipient theory of thermal phenomena is incommensurable with our thermal theory, there is no Florentine analog of "phlogiston." Their "degree of heat" is the ancestor of our "temperature" and "heat." In these cases, incommensurability arises from sets of core concepts being interrelated in different ways, and from several simultaneous differentiations and coalescences. Thus, although there may be no bodies such as "phlogiston" or "principle" in the child's language it remains an open empirical question whether cases of two-way incommensurable conceptual systems between children and adults are to be found.

### *How Would Incommensurability Arise (Empiricist Version)?*

The child learns language from adults; the language being spoken to the child is L2; why would the child construct a L1 incommensurable with L2? This is an empiricist objection to the possibility of incommensurability because it views the child as a blank state, acquiring the adult language in an unproblematic manner. But although children learn language from adults, they are not blank slates as regards their conceptual system. As they learn the terms of their language, they must map these onto the concepts they have available to them. Their conceptual system provides the hypotheses they may entertain as to possible word meanings. Thus, the language they actually construct is constrained both by the language they are hearing and the conceptualization of the world they have already constructed. Incommensurability could arise when this conceptualization is incommensurable with the C2 that L2 expresses.

Presumably, there are no phlogiston-type bodies in the child's L1, because the child learns language from adults. The child learning chemistry and the explanation for combustion would never learn words like "principle" or "phlogiston." However, it is an open empirical question whether the child assigns meanings to terms learned from adult language that are incommensurable with those of the adult.

### *How Would Incommensurability Arise (Nativist Version)?*

Empiricists question why the child, learning L2 from adults, might ever construct an incommensurable L1. Nativists worry how the developing mind, constrained by innate principles and concepts, would ever construct an L2 that is incommensurable with L1. This is Spelke's challenge, cited in the opening of the present chapter. Spelke does not deny the phenomenon of conceptual change in the history of science. That is, Spelke grants that innate constraints do not preclude the shift from the phlogiston theory to the oxygen theory, nor does she deny that this shift involves incommensurable concepts. Innate constraints do not preclude incommensurability *unless* children are different from scientists. Thus, Spelke's nativist objection requires the noncontinuity position, which is why she speculates that conceptual change requires mature scientists' explicit scrutiny of their concepts and their striving for consistency. Of course, merely positing noncontinuity begs the question.

In considering these speculations, we must remember that the child develops his or her conceptual system in collaboration with the adult culture. Important sources of information include the language of adults, the problems adults find worthy and solvable, and so on. This is most obvious in the case of explicit instruction in school, especially in math and science, but it is no less true of the commonsense theories of the social, biological, and physical worlds constructed by cultures. Not all commonsense knowledge of the physical, social, and biological worlds develops rapidly and effortlessly. One source of difficulty may be incommensurability between the child's conceptual system and that which the culture has constructed. Again, it is an open empirical issue whether commonsense conceptual development is continuous with scientific conceptual development in the sense of implicating incommensurability.

In this section, I have countered five arguments that we should not expect incommensurability between young children's and adult's conceptual systems. Of course, I have not shown that local incommensurability actually ever obtains. That is the task of the next section.

## 3. *The Evidence*

I have carried out case studies of children's conceptualization of two domains of nature, and in both cases some of the child's concepts are incommensurable with the adult's. One domain encompasses the child's concepts of *animal, plant, alive, person, death, growth, baby, eat, breathe, sleep,* and so forth (Carey 1985b, 1988). The other encompasses the child's concepts of *matter, material kind, weight, density,* and so on. (Carey, Smith, Sodian, Zaitchik, and Grosslight unpublished manuscript; Smith, Carey, and Wiser 1985; see also Piaget and Inhelder 1941). Here, I draw my examples from the latter case, for it includes physical concepts and thus bears more directly on Spelke's conjecture that commonsense physical concepts develop only through enrichment.

The central phenomenon that suggests developmental cases of incommensurability is the same as the one that suggests historical cases as well. The child makes assertions that are inexplicable to the adult, for example, that a particular piece of styrofoam is weightless or that the weight of an object changes when the object is turned on its side. Of course, such assertions do not in themselves demonstrate incommensurability. They raise three possibilities as to the relations between the child's conceptual system and the adult's:

1. The child is expressing false beliefs represented in terms of the same concept of weight as the adult's.
2. The child is expressing beliefs in terms of a different concept of weight from the adult, but the child's concept is definable in the adult vocabulary.
3. The child is expressing beliefs in terms of a different concept of weight from the adult; the child's and adult's concepts are incommensurable.

The only way to decide among these three alternatives is to analyze the child's and the adult's concepts of weight in the context of related concepts and the intuitive theories in which they are embedded.

Spelke's work on infants' conceptions of objects tells us that, from the earliest moment at which these conceptions have been probed, children represent objects as solid, in the sense that no part of one objects can pass through the space occupied by any part of another (see Spelke 1991). Work by Estes, Wellman, and Woolley (1989) shows that 3-year-olds draw a distinction between real physical objects, such as a real cookie, and mentally represented objects, such as an image of a cookie or a dream of a cookie. These very young children know that only the former can be seen and touched by both the child and other people, and only the latter can be changed by thought alone. The young child distinguishes physical objects from other entities in terms of properties that are at least precursors to those that adults use in drawing the distinction between material and immaterial entities. We shall see, however, that the child does not draw the material/immaterial distinction on the same basis as does the adult. Furthermore, the child's conceptual system represents several concepts undifferentiated relative to the adult's, and the differentiations are of the type that implicate incommensurability, that is, are like the *heat/temperature* case rather than the *poodle/collie* case. One example is the undifferentiated concept of *weight/density*. Like the concept of *heat/temperature* before Black, an undifferentiated *weight/density* concept does not remain a useful superordinate concept in the conceptual systems of those who have drawn the distinction.[3]

Like heat and temperature, weight and density are different sorts of physical magnitudes; weight is an extensive quantity, and density is an intensive quantity, and the two are interdefined. A single concept undifferentiated between the two is incoherent from the later point of view.

### 4. *Weight, Density, Matter, and Material Kind*

*Undifferentiated Concept: Weight/Density*

We require evidence in two steps to support the claim that weight and density are not differentiated by young children. To rule out the possibility that young children simply lack the concept *density*, we must show that heaviness relativized to size plays some role in their judgements. Indeed, Smith et al. (1985) found that many young children (3- to 5-year-olds) appear to lack the concept of density at all. Older children, in contrast, relativized weight to size in some of their judgments of heaviness. Secondly, once we have shown that *density* is not entirely absent, we must show that the child does not relate density to some physical phenomena and weight to others, but rather accounts for all heaviness-related phenomena in terms of an undifferentiated weight/density concept. Of course, one can never establish this beyond doubt; it is always possible that tomorrow somebody will find some limited contexts in which the child has systematically distinguished the two. But we (Smith et al. 1985) devised a series of tasks, both verbal and nonverbal, that probed for the distinction in the simplest ways we could think of. For example, we presented children with pairs of objects made of different metals, and asked "Which is heavier?" or "Which is made of the heavier kind of metal?" Nonverbal versions of the same task

3. The concept of *density* at issue here is a ratio of *weight* and *volume* and is a property of material kinds. We are not probing the more general abstract concept of density expressing the ratio of any two extensive variable, such as population density (people per area).

involved the child predicting which objects would make a sponge bridge collapse (weight being the relevant factor) and sorting objects into steel and aluminum families (density being the relevant factor). In the steel and aluminum family task, for example, the child was first shown several pairs of identically sized cylinders, and it was pointed out that steel is a much heavier kind of stuff than is aluminum. Children with an undifferentiated concept showed intrusion of absolute weight on judgments we would base on density; in this case, this meant sorting large aluminum cylinders into the steel family because they were heavy.

Smith, Snir, Grosslight, and Unger (1988) corroborated these results with other simple tasks. They provided children with scales and with sets of objects that varied in volume, weight, and material kind and asked them to order the objects by size, by absolute weight, and by density (explained in terms of heaviness of the kind of stuff). The ordering required no calculations of density; for instance, if one object is larger than another, but they weigh the same or the smaller is heavier, we can infer without calculation that the smaller is denser. Prior to instruction, few children as old as age 12 are able to correctly order the same set of items differently on the basis of absolute weight and density. Mistakes reveal intrusions of weight into the density orderings, and vice-versa. These results are underscored when children are asked to depict in a visual model the size, weights, and densities of a set of such objects. Only children who show in other tasks that they have at least partially differentiated weight and density produce models that depict, in some way or another, all three physical magnitudes.

Just as the Experimenters' undifferentiated *heat/temperature* concept led them into contradictions, children's *weight/density* concept leads them into outright contradiction. Smith et al. (1985) presented children in this conceptual state with two bricks, one of steel and one of aluminum. Though the steel brick was smaller, the two weighed the same, and children were shown that they balanced exactly on a scale. Children were probed: "How come these weigh the same, since one is so much bigger?" They answered, "Because that one (the steel) is made of a heavier kind of stuff," or "Because steel is heavier," or some equivalent response. They were then shown two bricks of steel and aluminum, now both the same size as each other, and asked to predict whether they would balance or whether one would be heavier than the other. Now they answered that they would weigh the same, "because the steel and aluminum weighed the same before" (Fig. 20.1).

Children give this pattern of responses because they do not realize that the claim that a given steel object weighs the same as a given aluminum object is not the same as that steel and aluminum weigh the same, even though they also understand that if a small steel object weighs the same as a large aluminum one, this is possible because steel is heavier than aluminum. It is not that children are unmoved by the contradiction in these assertions. They can be shown the contradiction, and because they, as well as adults, strive for consistency, they are upset by it. Drawing out contradictions that are inherent in current concepts is one of the functions of thought experiments (see Kuhn 1977; Nersessian 1992). Here, we have produced a concrete instantiation of a thought experiment for the child. Just as the Experimenters were unable to resolve the contradictions due to their undifferentiated *heat/temperature* concept, so too children cannot resolve the contradictions due to their undifferentiated *weight/density* concept.

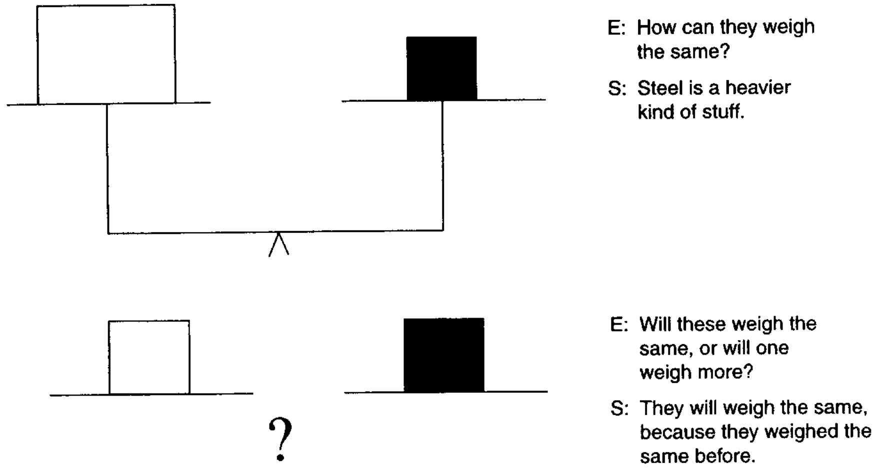


Figure 20.1
Concrete thought experiment.

*How an Undifferentiated Weight/Density Concept Functions*

The previous section outlined some of the evidence that 6- to 12-year-old children have a concept that is undifferentiated between weight and density. But how could such a concept function in any conceptual system, given the contradictions it leads the child into? The short answer is that the contexts in which the child deploys his or her weight/density concept do not, in general, elicit these contradictions. This is the same answer as for the Experimenter's *degree of heat* (undifferentiated between heat and temperature; Wiser and Carey 1983), or for Aristotle's *speed* (undifferentiated between average and instantaneous velocity; Kuhn 1997).

A sketch of the purposes for which children *do* use their concept provides a slightly longer answer. Like the Experimenters' *degree of heat*, the child's concept is *degree of heaviness*. Children appeal to heaviness of objects to explain some aspects of those objects' effects on themselves or on other objects. The greater an object's heaviness, the more difficult it is to lift, the more likely to hurt if dropped on one's toes, the more likely to break something else if dropped on it, and so on. Notice that "heavy," like other dimensional adjectives such as "big," is a relative term. Something is heavy relative to some standard, and the child can switch fluidly from one way of relativizing heaviness to another. An object can be heavy for objects of that type (e.g., a heavy book), heavy for the objects on the table, heavy for me but not my mother, or heavy for objects of that size. For the child with an undifferentiated weight/density concept, relativizing heaviness to a standard determined by size is no different from their ways of relativizing heaviness. Children differentiate *weight* and *density* as they realize that relativizing weight to size produces an independent physical magnitude, that is, one related in systematic ways to distinct phenomena in the world.

The full answer to how children can have an undifferentiated weight/density concept that functions effectively within their conceptual system will require a description of their conceptual system. The claim that weight and density are not differentiated does not exhaust the differences between the child's concept and the adult's; indeed, it could not. Because an undifferentiated weight/density concept is incoherent from the adult's point of view, it must be embedded in a very different conceptual system to function coherently in the child's. We should expect, therefore, that the child's concept of heaviness differs from the adult's in many ways, beyond it's being undifferentiated between weight and density.

*The Material/Immaterial Distinction*

The concepts of weight and density are embedded in an intuitive theory of matter. Weight is an extensive property of material entities; density an intensive property of material entities. Weight is proportional to quantity of matter; density is the ratio of quantity of matter to volume. The concepts of weight, density, matter, and quantity of matter have a long intellectual history (see Toulmin and Goodfield 1962; Jammer 1961, for comprehensive reviews). As Jammer (1961) told the story, the late 19th century saw the flowering of the substantial concept of matter, which identified matter and mass. The concept of inertial mass had been formulated by Kepler and systematized by Newton, who also fused it with the medieval concept of "quantity of matter." A typical statement from the turn of the century was, "If I should have to define matter, I would say: Matter is all that has mass, or all that requires force in order to be set in motion" (Charles de Freycinet 1896, quoted in Jammer 1961, p. 86). According to this view, mass is the essential property of matter and provides a measure of quantity of matter. In a given gravitational field, weight is an extensive quantity proportional to mass.

Clearly, prior to the formulation of the concept of mass, having mass could not be taken as the essence of material entities. And indeed, prior to the formulation of the concept of mass, weight was not seen as a candidate measure of quantity of matter, nor was having weight (even on Earth) seen as necessary and sufficient for an entity's being material (Jammer 1961). The Greeks and the medieval scholastics had different concepts of matter and weight from post-Newtonian physicists. According to Jammer, Aristotle had no concept of quantity of matter, and he saw weight as an accidental property of some material entities, akin to odor. Even if the Greeks had a concept of quantity of matter, weight could not have served as its measure, because some material entities, such as air, were thought to possess intrinsic levity. For the Greeks, weight was not an extensive quantity. There were no fixed units of weight; in practical uses, even within the same nation, different substances were weighed in terms of different standards. The weight of material particles were thought to depend on the bulk of the object in which they were embedded. That is, Aristotle thought that a given lump of clay would itself weigh more when part of a large quantity of clay than when alone. Neither did the alchemists consider weight to reflect quantity of matter; they fully expected to be able to turn a few pounds of lead into hundreds of pounds of gold (Jammer 1961).

Density also was taken to be an irreducible intensive quality, like color, odor, and other accidents of matter. Density was not defined as mass/volume until Euler did so; what was actually quantified by the ancients was specific gravity (the ratio of a substance's density to that of water), not density. For example, Archimedes never used a term for density in his writings (Jammer 1961).

If weight was not an essential property of material entities, what was? There were many proposals. Euclid proposed spatial extent—length, breadth, and depth. This was one dominant possibility throughout Greek and medieval times. Galileo listed shape, size, location, number and motion as the essential properties of material entities—spatial, arithmetic, and dynamic properties. The spatial notions included impenetrability; that is, material entities were seen to uniquely occupy space. In another thread of thought, material entities were those that could physically interact with other material entities (Toulmin and Goodfield 1962). Again, weight was seen as irrelevant; according to this view, heat while weightless, is certainly material. Finally, another line of thought posited being inert, or passive, as the essence of matter. This was the precursor to the concept of mass; material entities are those that require forces for their movement (Kepler) or forms for their expression (Aristotle and the scholastics).

The substantial conception of matter (the identification of matter with mass), occupied a brief moment in the history of science. Since Einstein, the distinction between entities with mass and those without is not taken to be absolute, because mass and energy are intraconvertible. It is not clear that the distinction between material and immaterial entities plays an important role in today's physics, given the existence of particles with no rest mass, such as photons, which are nevertheless subject to gravity, and, as Jammer (1961) pointed out, the concept of mass itself is far from unproblematic in modern physics.

Given the complex history of the concept of matter, what conception of matter should we probe for in the child? *Ours* would be a good bet, i.e., that of the nonscientific adult. What is the adult's intuitive conception of matter, and how is it related to the commonsense concepts of weight and density? Although this is an empirical question, I shall make some assumptions. I assume that commonsense intuitive physics distinguishes between clearly material entities, such as solid objects, liquids, and powders, on the one hand, and clearly immaterial entities, such as abstractions (height, value) and mental entities (ideas), on the other. I also assume that adults conceptualize quantity of matter. Probably, the essential properties of matter are thought to include spatial extent, impenetrability, weight, and the potential for interaction with other material entities. Probably, most adults do not realize that these four properties are not perfectly coextensive. Weight is probably seen as an extensive property of material entities, proportional to quantity of matter, whereas density is an intensive property, seen as a ratio of quantity of matter and size. This view is closely related to the substantial conception of matter achieved at the end of the 19th century, but it differs from that in not being based on the Newtonian conception of mass and being unclear about the status of many entities (e.g., gasses, heat, etc.).

There are two reasons why commonsense physics might be identified so closely with one moment in the history of science. First, commonsense science is close to the phenomena; it is not the grand metaphysical enterprise of the Greek philosophers. For example, in two distinct cases, commonsense science has been shown to accord with the concepts employed in the first systematic exploration of physical phenomena. Commonsense theories of motion share much with medieval impetus theories (e.g., McKloskey 1983), and commonsense thermal theories share much with the source-recipient theory of the Experimenters (see Wiser 1988). Both of these theories require a concept of quantity of matter. For example, the impetus theory posits a resistance to impetus that is proportional to quantity of matter, and the source-recipient theory of heat posits a resistance to heat that is proportional to quantity of matter. That untutored adults hold these theories is one reason I expect them to have a pre-Newtonian conception of quantity of matter. Second, the developments of theoretical physics find their way into commonsense physics, albeit at a time lag and in a watered down and distorted version. The mechanisms underlying this transmission include assimilating science instruction (however badly), making sense of the technological achievements made possible by formal science, and learning to use the measuring devices of science, such as scales and thermometers.

*The Child's Material/Immaterial Distinction*

We have four interrelated questions. Do young children draw a material/immaterial distinction? If yes, what is the essence of this distinction? And finally, do they conceptualize "amount of matter?" If so, what is its measure?

Estes et al. (1989) claimed that preschool children know that mental entities are immaterial; Piaget (1960) claimed that, until age 8 or so, children consider shadows to be substantial, a claim that was endorsed by DeVries (1987). These works credit the young child with a material/immaterial distinction and with one true belief (ideals are immaterial) and one false belief (shadows are material) involving the concept of materiality. Assuming that children realize that shadows are weightless, this latter belief would indicate that, like Aristotle, they consider weight to be an accidental property of material entities. But is it true they draw a material/immaterial distinction, and if so, on what grounds?

The claim of Estes et al. is based on the fact that children distinguish physical objects, such as cookies, from mental entities, such as dreams and pictures in one's head. Estes et al. probed this distinction in terms of the properties of objective perceptual access (can be seen both by the child and others) and causal interaction with other material entities (cannot be moved or changed just by thinking about it). The clever studies of Estes et al. certainly show that the child distinguishes objects from mental representations of objects in terms of features relevant to the material/immaterial distinction. But many distinctions will separate some material entities from some immaterial entities. Before we credit the child with a *material/immaterial* distinction, we must assess more fully the extension of the distinction, and we must attempt to probe the role the distinction plays in the child's conceptual system.

Shadows' materiality would be consistent with the essential properties of material entities being public perceptual access and immunity to change as a result of mental effort alone. Piaget's and DeVries' claim is based on children's statements like the following: "A shadow comes off you, so it's made of you"; "If you stand in the light, it can come off you"; "It's always there, but the darkness hides it"; or "The light causes the shadow to reflect, otherwise it is always on your body" (DeVries 1987). Such statements show that children talk as if shadows are made of some kind of substance and that they attribute to shadow some properties of objects, such as permanent existence. DeVries studied 223 children, ages 2 to 9, and only 5% of the 8- and 9-year-olds understood that shadows do not continue to exist at night, in the dark, or when another object blocks the light source causing the shadow. In discussing the question of the continued existence of shadows, virtually all children spoke of one shadow being covered by another, or of the darkness of two shadows being mixed together, making it impossible to see the shadow, even though it was still there. A similar problem arises in interpreting these data as arises in interpreting those of Estes et al. These studies show that the child attributes to shadows some properties of material entities (i.e., independent existence and permanance), but what makes these properties tantamount to *substantiality*? It is not enough that these properties differentiate some entities we consider substantial, or material, from some we do not. Many properties do that.

We must assess whether the distinction between material and immaterial entities plays any role in the child's conceptual system. One reflection of such a role would be that children would find it useful to lexicalize the distinction. Preschool children surely do not know the word "matter" or "material," but they probably do know "stuff" and "kind of stuff." Have they mapped these words onto the distinction studied by Estes et al.? Do they consider shadows made of some kind of stuff, as Piaget and De Vries claimed? In the context of an interview about kinds of stuff such as wood, metal, and plastic, Smith et al. (1985) asked 4- to 9-year-olds whether shadows are made of some kind of stuff. About three fourths of the 4- to 7-year-olds replied "Yes," and most volunteered, "Out of you and the sun." Although this may reflect their considering shadows material, it seems more likely to reflect their understanding the question to be whether and how one can make a shadow.

In a recent study, my colleagues and I attempted to address directly whether the child distinguishes between entities made of some kind of stuff and entities not made of some kind of stuff, and if so, on what basis. We introduced children from the ages of 4 through 12 to the issue by telling them that some things in the world, such as stones and tables and animals, are made of some kind of stuff, are material, and are made of molecules, whereas other things that we can think of, like sadness and ideas, are not made of anything, are not material, and are not made of molecules (Carey et al. unpublished manuscript). We encouraged children to reflect on this distinction and to repeat our examples of material and immaterial entities. We then asked them to sort the following into two piles: (a) material things, like stones, tables, and animals and (b) immaterial things, like sadness and ideas: car, tree, sand, sugar, cow, worm, styrofoam, Coca Cola, water, dissolved sugar, steam, smoke, air; electricity, heat, light, shadow, echo, wish, and dream. We will credit children with the distinction if they sort objects, liquids, and powders in the material piles and wish and dream in the immaterial pile. Where they place the remaining items will provide some information concerning the properties they consider central to the distinction.

As can be seen from Table 20.1, our instructions led to systematic sorting at all ages. At all ages, over 90% of the placements of the car, the tree, and Styrofoam were into the material pile, and at all ages except age 6, less than 15% of the placements of wish and dream were into this pile. Children understood something of the introductory instruction and certainly distinguish solid inanimate objects from abstract entities and mental representations. Shadows were not considered material; at all ages except age 4, shadows and echos patterned with wishes and dreams. These data do not support Piaget's and DeVries' claim that young children consider shadows to be substantial. Nonetheless, many of the younger children revealed very different bases for their sorts than did the older children. Around one tenth of the 4- and 6-year-olds answered randomly. In addition, half of the preschool children took only solid inanimate objects plus powders as material. That is, 50% of the 4-year-olds denied that animals and liquids are material, including a few who also denied that sand and sugar are; 13% of the 6-year-olds also showed this pattern; see Table 20.2. These data are striking, because the introduction of the material/immaterial distinction explicitly mentioned animals as examples of material entities. These children seemed to focus on the locution "made of some kind of stuff" and therefore answered affirmatively either if they could think of the material of which something is made (many commented

Table 20.1
% judged material

| | Age | | | |
|---|---|---|---|---|
| | 4 | 6 | 10 | 12 |
| Car, tree, styrofoam | 93 | 96 | 91 | 100 |
| Sand, sugar | 65 | 94 | 95 | 100 |
| Cow, worm | 55 | 81 | 95 | 100 |
| Coca Cola | 30 | 88 | 100 | 100 |
| Water | 40 | 25 | 90 | 100 |
| Dissolved sugar | 63 | 63 | 55 | 88 |
| Steam, smoke, air | 20 | 25 | 30 | 61 |
| Electricity | 40 | 75 | 73 | 63 |
| Heat, light | 30 | 38 | 41 | 31 |
| Echo, shadow | 25 | 25 | 9 | 13 |
| Wish, dream | 5 | 19 | 5 | 13 |

Table 20.2
Individual pattern analysis (%)

| | Age 4 $n = 10$ | Age 6 $n = 8$ | Age 10 $n = 11$ | Age 12 $n = 8$ |
|---|---|---|---|---|
| adult, mass criterial | 0 | 0 | 9 | 0 |
| mass, critical; gasses massless | 0 | 0 | 9 | 38 |
| physical consequences—includes gasses, electricity, light, etc. | 0 | 0 | 0 | 63 |
| physical consequences—excludes gasses | 40 | 75 | 82 | 0 |
| denies liquids, animals, gasses, and immaterial entities | 50 | 13 | 0 | 0 |
| random | 10 | 13 | 0 | 0 |

that trees are made of wood) or if they thought of the entities as constructed artifacts. Another reflection of this construal is seen in the 6-year-olds' responses to Coke (88% sorted as material) compared to water (25% sorted as material). Children could think of ingredients of Coke (sugar and syrup), but saw water as a primitive ingredient, thus not made of any kind of stuff. This construal also contributed to the 6-year-old's affirmative judgments on wish and dream; some children commented that dreams are made of ideas. Thus, among the youngest children there were considerable problems understanding or holding onto what distinction was being probed. Sixty percent of the 4-year-olds and 25% of the 6-year-olds showed no evidence of a conception of matter that encompassed inanimate objects, animal, liquids, and powders. These children had not mapped the properties probed by Estes et al. onto their notion of "stuff."

However, 40% of the 4-year-olds, 75% of the 6-year-olds, and 100% of the 10–11-year-olds provided systematic sorts that clearly reflect a concept of matter. Clearly, weighing something, or having mass, is not coextensive with the entities children judge material. It is only the oldest children who sometimes claimed that all weightless entities were not material (38% of the oldest group, Table 20.2). As can be seen in Table 20.2, only one child in the whole sample had an adult pattern of judgments.

Three groups of entities are reflected in the sorts: (solids, liquids and powders on the one hand, and echo, shadow, wish and dream on the other, with all others firmly in between). For children under 12, electricity, heat, and light are equally or more often judged material than are dissolved sugar, steam, smoke, and air (Table 20.1). Further, all children under 12 judged some immaterial entities (such as heat) material *and* some material entities (such as air) immaterial. In their justifications for their judgments, children mainly appealed to the perceptual effects of the entities—they mentioned that one can see and touch them. One child in a pilot study articulated the rule that one needs two or more perceptual effects for entities to be material. You can see shadows, but cannot smell, feel, or hear them; you can hear echos but cannot see, smell, or touch them; therefore, shadows and echos are not material. Nor is air. But heat can be seen (heat waves) and felt, so heat is material.

To sum up the data from the sorting task, of the youngest children (ages 4 to 6), a significant portion do not know the meaning of "stuff" in which it is synonymous with "material." This leaves open the question of whether they draw the material/immaterial distinction, even though this task failed to tap it. However, about half of the younger children and all of the older ones did interpret "stuff" in the sense intended, revealing a material/immaterial distinction. Up through age 11, the distinction between material and immaterial entities is not made on the basis of weight. Only at ages 11–12 are there a few children who take all and only entities that weigh something as material.

### *Weight and Materiality, Continued*

The sorting data show that early elementary children do not take an entity's weighing something as necessary for materiality (in the sense of being make of some kind of stuff). From ages 4 through 11, virtually all children who deemed solids, liquids, and powders material also judged some weightless entities (electricity, heat, light, echoes, or shadow) material. However, they might hold a related belief. They may see weight as a property of all prototypical material entities (solids, liquids and powders). Smith et al. (1985) provided data that suggest that young children do not expect even this relation between materiality and weight. When given a choice between "weighs a lot, a tiny amount, or nothing at all," children judged that a single grain of rice, or a small piece of Styrofoam, weighed nothing at all. We probed for a similar judgment from those children who had participated in the material/immaterial sorting task. Virtually all had judged Styrofoam to be material (Table 20.1). We began with a sheet of Styrofoam that measured 12" by 12" by 1/2" and asked whether it weighed a lot, a little, a tiny amount, or nothing at all. If children judged that it weighed a little, we showed a piece half that size and asked again. If that was judged as weighing at least a tiny amount, a small piece the size of a fingertip was produced, and the question was repeated. Finally, the child was asked to imagine the piece being cut again and again until we had a piece so small we could not see it with our eyes, and asked if that would weigh a lot, a little, or nothing at all—whether we could ever get to a piece so small it would weigh nothing at all.

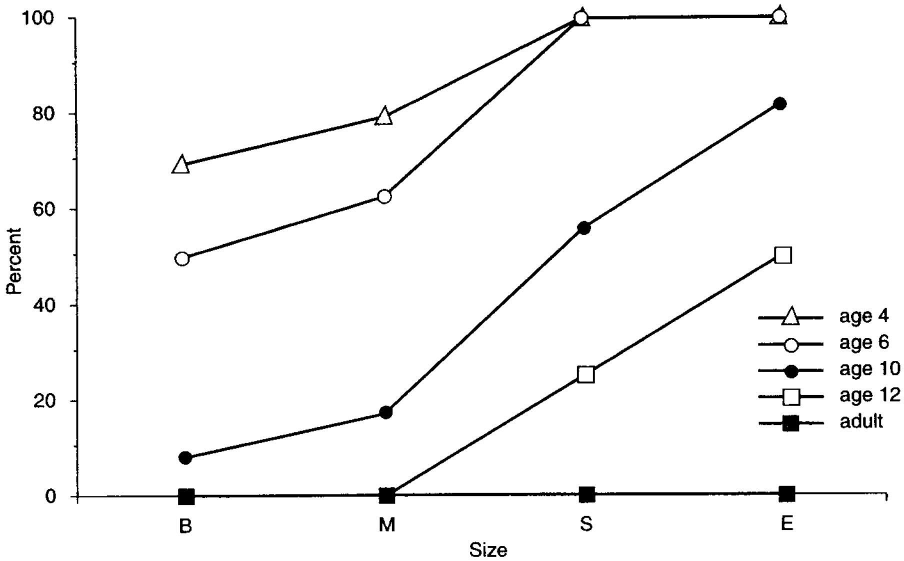


Figure 20.2
Weight of Styrofoam. Percent judging piece of Styrofoam weighs nothing at all as a function of size of piece. B, big; M, medium; S, small; E, ever, if one kept cutting it in half, repeatedly.

Smith et al.'s results were confirmed (Fig. 20.2). More than half of the 4-year-olds and fully half of the 6-year-olds judged that the *large* piece of Styrofoam weighed nothing at all, and all 4- to 6-year-olds judged that the small piece weighted nothing. Half of the 10–11-year-olds judged that the small piece weighed nothing at all, and almost all judged that if one kept dividing the Styrofoam, one would eventually obtain a piece that weighed nothing. Not until age 12 did half of the children maintain that however small the piece, even one so small one could no longer see it, it would weigh a tiny, tiny amount.

These data are important beyond showing that children consider an entity's weighing something as unrelated to its being material. They show that children, like the Greeks, do not take weight as a truly extensive property of substances. They do not conceive of the total weight of an object as the sum of weights of arbitrarily small portions of the substance from which it is made. This is one very important way in which the child's *degree of heaviness* differs from the adult's *weight*. The child's *degree of heaviness* is neither systematically intensive nor systematically extensive, as is required if the child's concept is undifferentiated between *weight* and *density*.

*Physical Objects' Occupying Space*

We do not doubt that even 4-year-olds know some properties that solids, liquids, and powders share, even if being "made of some kind of stuff" and having weight are not among these properties. Presumably, young children extend the properties of physical objects studied by Estes et al. (1989) to liquids and powders: public access and nonmanipulation by thought alone, for example. Another place to look might be a generalization of the infants' solidity constraint (see Spelke 1991). Infants know that one physical object cannot pass through the space occupied by another; we would

Table 20.3
Occupy space: Can steel and X fit in box at same time?

| | No (%) | | |
|---|---|---|---|
| | Steel and wood | Steel and water | Steel and air |
| Age 4 ($n = 10$) | 100 | 90 | 0* |
| 1st grade ($n = 8$) | 100 | 100 | 25 |
| 5th grade ($n = 11$) | 100 | 100 | 55 |
| 7th grade ($n = 8$) | 100 | 100 | 62.5 |

*$n = 5$; The remaining five 4-year-olds denied there was air in the box.

certainly expect 4-year-olds to realize the related principle that no two objects can occupy the same space at the same time, and they might extend this principle to liquids and powders. We assessed this question by asking our subjects to imagine two pieces of material, one wood and one metal, cut to fill entirely the inside of a box. They were then asked whether we could put the wood and the metal in the box at the same time. No children had any doubts about this question; they answered that they both could not fit in at the same time (Table 20.3). When asked to imagine the box filled with water and then probed as to whether the steel piece and the water could be in the box at the same time, they all (except one 4-year-old who said that both could be in the box at the same time because the water would become compressed) again said no, that the water would be pushed out (Table 20.3).

Children are confident that solids and liquids (and, I am sure, though we did not probe it, materials such as sand as well) uniquely occupy space. However, it is unlikely that this property defines a material/immaterial distinction for them. To assess that, we would have to see whether those that think electricity, heat, light, echos, or shadows to be material also consider these to occupy space. Still, these data confirm our suspicion that children see physical objects, liquids, and powders as sharing properties relevant to the material/immaterial distinction. Having weight is simply not one of these properties.

*A Digression: An Undifferentiated* Air/Nothing *Concept*

The last questions about the box concerned air. Children were asked, of the apparently empty box, whether there was anything in it at the moment, and when they said no, we said, "What about air?" Except for half of the 4-year-olds, who denied there was air in the box and insisted that there was nothing in it, all children agreed that the box contained air. All who agreed were asked whether one could put the steel in the box at the same time as the air. If they said yes, they were further probed as to whether the steel and air would be in the box, then, at the same time. As can be seen from Table 20.3, the vast majority of the 4-year-olds and 6-year-olds thought that air and steel could be in the box at the same time, explaining, "Air doesn't take up any space," "Air is all over the place," "Air is just there—the metal goes in, air is still there," "Air isn't anything," and so on. One child said baldly, "Air isn't matter." Almost half of the 10–12-year-olds also provided this pattern of response.

The sorting task also suggests that young children consider air not material—air was judged to be made of some kind of stuff by none of the 4-year-olds, 10% of the

6-year-olds, and 36% of the 10–11-year-olds. Only 12-year-old subjects judged air to be made of some kind of stuff (75%) and also maintained that the steel would push the air out, just as it would the water (65%). Although the characterization of the child as believing air to be immaterial is easy enough to write down, a moment's reflection reveals it to be bizarre. If air is not material, what is it? Perhaps children consider air to be an immaterial physical, entity, like a shadow or an echo. But several children said outright, "Air is nothing; Air isn't anything." However, "air" is not simply synonymous with "nothing," or "empty space," for children this age know that there is no air on the moon or in outer space, that one needs air to breathe, that wind is made of air, and so on. Indeed, in a different interview in which we probed whether children of this age considered dreams and ideas to be made of some kind of stuff, an interview in which "air" was never mentioned, several different children spontaneously offered "air" as the stuff of which dreams and ideas are made of. This set of beliefs reflects another undifferentiated concept, *air/nothing* or *air/vacuum* incommensurable with the concepts in the adult conceptualization of matter.

*Interim Conclusions—the Material/Immaterial Distinction*

Children distinguish solids, liquids, and powders, on the one hand, from entities such as wishes and dreams, on the other, in terms of properties related to the distinction between material and immaterial entities. These include uniquely occupying space, and (probably) public perceptual access and not being manipulable by thought alone. Not all 4–6-year-olds have related this distinction to the notion of "stuff," so the data available at this point provide no evidence that these properties determine a *material/immaterial* distinction, rather than, for example, an undifferentiated *real/unreal* distinction. Some children of these ages, and all children in our sample of ages 10 and older, have related this distinction to the notion of "stuff" but do not yet see weight as one criterion for materiality.

*Taking up Space: Matter's Homogeneity*

Although young children may not draw a distinction between material and immaterial entities, they do conceptualize kinds of stuff such as plastic, glass, wood, sand, and water. They distinguish objects from the stuff of which they are made, realizing that the identity of an object does not survive cutting it into many small pieces, but the identity of the stuff is not affected. However, there is some question as to the limits of their ability to preserve identity of stuff as it is broken into smaller and smaller pieces. Smith et al. (1985) suggested that perhaps young children cannot conceive of substances as composed of *arbitrarily* small portions, each of which maintains the identity of the substance and some of its substance-relevant properties. In other words, they may not grasp that stuff is homogeneous. This could underly their lack of understanding that the total weight of an object is the sum of the weights of small portions. Alternatively, the problems young children have with conceptualizing the weight of tiny portions of matter could be independent of a homogeneous conception of substance.

Children's commitment to solids and liquids occupying space led us to probe their understanding of homogeneity in this context (Carey et al. unpublished manuscript). Our first method of doing so drew on the weight probes described before. We asked children whether the big piece of Styrofoam took up a lot of space, a little space, or no space at all. We then repeated that question concerning the small piece, the tiny

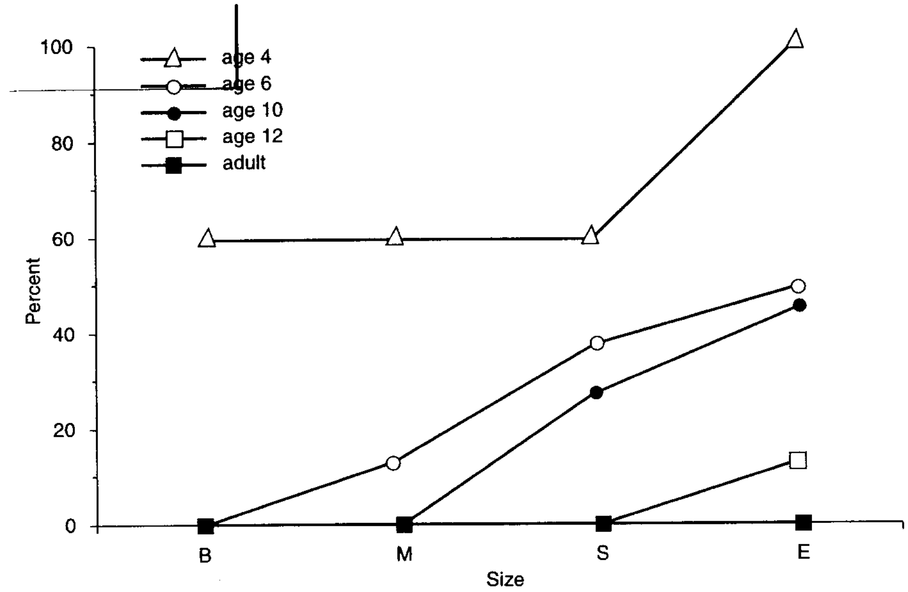


Figure 20.3
Styrofoam's taking up space. Percent judging piece of Styrofoam takes up no space at all as a function of size of piece. B, big; M, medium; S, small; E, ever, if one kept cutting it in half, repeatedly.

piece, and imagined halves and halves again until we got a piece so small one could not see it with one's eyes.

Compare Fig. 20.3 to Fig. 20.2. At all ages, children revealed a better understanding of homogeneity in the context of the question of whether a piece of Styrofoam occupies space than they did in the context of the question of whether a piece of styrofoam weighs anything. Twelve-year-olds were virtually perfect on the task; only one said that one could arrive at a piece of Styrofoam so small that it would not take up any space at all. More significantly, fully half of the 6- and 10–11-year-olds made these adult judgments. Only 4-year-olds universally failed; all said that if one arrived, by cutting, at a piece too small to see with one's eyes, that piece would not take up any space. By this measure then, almost all 12-year-olds, and half of the children between ages 6 and 12, understand that solid substances are continuously divisable, and that an arbitrarily small piece of substance still occupies a tiny tiny amount of space. They understand substances to be homogeneous. Equally important, by this measure, 4-year-olds do not have this understanding.

Not all children understood the locution "take up space." As Nussbaum (1985) pointed out, children lack the Newtonian conception of space as a geometric construction that defines points that may or may not be occupied by material bodies. Because we could see that some children were not understanding what we were getting at, we devised another question to probe children's understanding of the homogeneity of matter. We presented an iron cylinder, told children that it was made of iron, and asked whether they could see *all* the iron in the bar. If children responsed "no," they were then shown a much smaller cylinder, and the question was repeated. Next they were shown an iron shaving, and the question repeated, and finally were

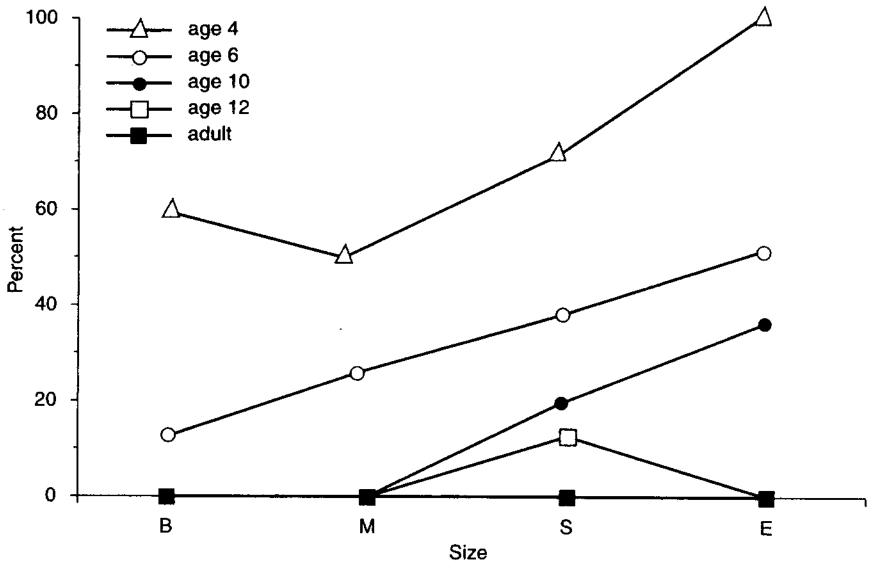


Figure 20.4
Visibility of all the iron. Percent judging one can see all the iron as a function of the size of the piece of iron. B, big; M, medium; S, shaving; E, ever, if one kept cutting it in half, repeatedly.

asked to imagine halving the iron repeatedly, probed as to whether one could ever get a piece small enough so that (with a microscope) one could see all the iron. A commitment to the continuity and homogeneity of matter is revealed in the response that however small the piece, there will always be iron inside. Of course, matter is particulate, not continuous. In principle, one could arrive, by the process of dividing, at a single atom of iron, in which there would be no iron inside. Children are often taught the particulate theory of matter beginning in seventh to ninth grades; work by science educators shows that children of these ages are deeply committed to a continuous theory of matter (e.g., Novick and Nussbaum 1978, 1981; Driver et al. 1987).

There were two types of answers that showed children to be thinking about the iron as an object, rather than as a continuous substance: "Yes, you can see all the iron," or "No, because you can't see the bottom," or "Because there is some rust on it." This probe for an understanding of homogenity and continuity of matter reveals the same developmental pattern as did the questions of whether small pieces of matter occupy space (Fig. 20.4; compare with Fig. 20.3.) All of the 12-year-olds said that one could never see all the iron, no matter how small the piece, because there would always be more iron inside. More than half of the 6–11-year-olds also gave this pattern of responses. Only 4-year-olds universally failed. A majority of the preschool children claimed that one could see all the iron in two large cylinders, more said so for the shaving, and virtually all said that one would eventually get to a speck small enough so one could see all the iron.

Figures 20.3 and 20.4 reveal nearly identical patterns. An analysis of consistency within individuals corroborates this result. Those children who revealed an understanding of continuity and homogeneity on the "see all the iron" task also did so on the "Styrofoam occupies space" task, and those who failed on one failed on the other.

The relationship holds even when the 4-year-olds (almost all failing both tasks) and the 12-year-olds (almost all succeeding at both tasks) are removed from the analysis ($p < .05$, chi-square). The two tasks are really quite different from each other, so this within-child consistency strengthens our conclusion that 4-year-olds do not grasp the continuity and homogeneity of solid substances, that half of early elementary aged children do, and that by age 12 virtually all children have constructed such an understanding of solid substance.

An understanding of substances as continuous and homogeneous may well be a conceptual prerequisite to an extensive understanding of weight. If children cannot think of a piece of iron as composed of arbitrarily small portions of iron, then they would not be able to think of the weight of an object as the sum of weights of arbitrary portions of the substance from which it is made. The data in Figs. 20.3 and 20.4 show that all 4-year-olds and half of the 6–11-year-olds lack this prerequisite for an extensive understanding of weight. But the comparisons between these data and those in Fig. 20.2 show that more is required for a reconceputalization of *degree of heaviness* as true *weight*. What might that be?

My answer is speculative, going well beyond the data at hand. My guess is that an understanding of substance as continuous and homogenous is a prerequisite for a concept of *quantity of substance* or *quantity of matter*. Even after one has formulated the concept of *quantity of matter*, the question of heaviness being an accidental property of matter is open. In the course of differentiating *weight* and *density*, the child will see that volume cannot be a measure of quantity of matter, leading the child to be open to an extensive conception of weight as a measure of quantity of matter.

*Mathematical Prerequisites*

Like the Experimenters' *degree of heat*, the child's *degree of heaviness* is not a fully quantitative concept. The child's *degree of heaviness* is certainly ordered. Children understand that one object (A) can be heavier than another (B), and they expect relative heaviness to be reflected in measurements of weight—if A weighs 250 grams, then B will weigh less than 250 grams. They take this relation to be transitive and asymmetric. However, the limits of children's quantification of degree of heaviness are revealed in their willingness to judge that a piece of substance 250 grams could be broken into 10 parts, each of which weighs nothing.

A true understanding of the extensivity of weight requires an understanding of division, a mathematical concept that is very difficult for most elementary school children (see Gelman 1991). And a quantitative, extensive conception of weight is clearly required for a quantitative conception of density. This further requires an understanding of ratios and fractions, also conceptually difficult for children in these age ranges (see Gelman 1991). Thus, as Piaget and Inhelder (1941) argued cogently, a quantitative understanding of density requires mathematical concepts that do not emerge in most children until early adolescence.

Black differentiated heat from temperature in the course of attempting to measure each independently from each other and relating each quantified magnitude to distinct thermal phenomena. The full differentiation of weight and density is achieved by children during science instruction, in the course of similar activities. Unlike Black, the young elementary-school-aged child lacks the mathematical tools for this achievement. The experimenters faced theory-specific conceptual barriers to differentiating heat and temperature. Similarly, the child faces theory-specific conceptual barriers to differentiating weight and density. But the child also lacks tools of wide application (Carey 1985a)—here, mathematical tools—important for the reconceptualization. In this sense, there is domain-general limitation on the young child's understanding of matter, just as Piaget and Inhelder (1941) argued.

### 5. *Conclusions*

Concepts change in the course of knowledge acquisition. The changes that occur can be placed on a continuum of types—from enrichment of concepts that maintain their core to evolution of one set of concepts into another that is incommensurable with the original. In this chapter, I have explored Spelke's conjecture that spontaneous development of physical theories involves only enrichment. I argued, contra Spelke, that the child's intuitive theory of physical objects is incommensurable with the adult's intuitive theory of material entities.

As in cases of conceptual change in the history of science, this case from childhood includes differentiations where the undifferentiated concepts of C1 play no role in the adult C2 and are even incoherent from the vantage point of C2. *Weight/density* and *air/nothing* were the examples sketched here. The child's language cannot be translated into the adult's without a gloss. One cannot simply state the child's beliefs in terms of adult concepts—the child believes that air is not material, but the "air" in that sentence as it expresses the child's belief is not our "air," and the "material" is not our material." Similarly, the child believes that heavy objects sink, but the "heavy" in that sentence as it expresses the child's belief is not our "heavy." I can communicate the child's concepts to you, but have provided a gloss in the course of presenting the patterns of judgments the child makes on the tasks I described. To communicate the child's concept of *degree of heaviness*, I had to show its relation to the child's concepts of *density* and *substance*, for all these differ from the adult's concepts and are interrelated differently than in the adult conceptual system. These are the hallmarks of incommensurable conceptual systems.

Spelke might reply that the conceptual change described here was *originally* achieved by metaconceptually aware scientists, and that children only achieve it, with difficulty, as a result of schooling. Thus, it does not constitute a counterexample to her claim that spontaneous knowledge acquisition in childhood involves only enrichment. This (imaginary) reply misses the mark in two ways. First, even if the original development of the lay adult's concept of matter was achieved by metaconceptually sophisticated adults, and only gradually become part of the cultural repetoire of lay theorists, it is still possible that spontaneous (in the sense of unschooled) conceptual change occurs as children make sense of the lay theory expressed by the adults around them. Second, the construction of a continuous, homogeneous conception of substances occurs spontaneously between ages 4 and 11, in at least half of children in our sample. This is not taught in school; indeed, this theory is known to be false by science teachers. Similarly, in Smith et al. (1985), roughly half of the children had differentiated weight from density by age 9, before they encountered the topic in the school curriculum. True, many children require intensive instruction to achieve this differentiation (see Smith et al. 1988). What we have here is analogous to Gelman's findings on fractions; some elementary-aged children construct a conceptually deep understanding of fractions from minimal exposure to the topic, and others do not (Gelman 1991).

Spelke's speculations concerning spontaneous knowledge acquisition include two nested theses. She argues that conceptual change that is more extreme than enrichment (a) does not occur in the course of spontaneous development of physical concepts, in general, and (b) does not occur in the spontaneous development of the concept *physical objects*, in particular. It is the first thesis I have denied in this chapter. Let us now turn to the second. True, babies and adults see the world as containing objects that obey the solidity and spatio-temporal continuity principles. But for adults, these principles follow from a more abstract characterization of objects as material, and in the adult version of the principles, liquid, powders, and even gasses obey the same principles. At the very least, conceptual change of the second and their degrees has occured—what the baby takes as the core properties of objects are seen by the adult to be derived from more fundamental properties. And adults have constructed a fundamental theoretical distinction, material/immaterial, unrepresented by babies.

I would speculate that the conceptual evolution between the baby's concepts and the adult's passes through at least two major hurdles. Objects, for babies, are bounded, coherent, wholes and, as such, are totally distinct from liquids, gels, powder, and other nonsolid substances. The distinction between objects and nonsolid substances is very salient to young children; it conditions hypotheses about word meanings and relates to the quantificational distinction between entities quantified as individuals and entities not quantified as individuals (Soja, Carey, and Spelke 1991; Bloom 1990). It seems possible that young children believe that objects can pass through the space occupied by liquids, because they experience their own bodies passing through water and objects sinking through water. The first hurdle is the discovery that, in spite of these differences, physical objects and nonsolid substances share important properties, making liquids and powers *substantial* in the same sense as are objects. By age 4, children apparently understand that liquids uniquely occupy space; it is not clear whether younger children do.

Liquids and powders are not quantified as individuals precisely because they have no intrinsic boundaries; they can be separated and recoalesced at will. The quantificational distinction between nonsolid substances and objects supports seeing nonsolid substances as homogeneous and continuous and not seeing objects in this light. The second hurdle involves extending this conception of nonsolid substances to solid substances. The data reviewed heretofore shows that by ages 6 to 11, only half of the children in our sample had achieved this extension.

Changes of this sort go beyond mere enrichment. New ontological distinctions come into being (e.g., material/immaterial), and in terms of this distinction, entities previously considered ontologically distinct (e.g., objects and water) are seen to be fundamentally the same. The acquisition of knowledge about objects involves more than changes in beliefs about them. The adult can formulate the belief that "Objects are material"; the infant cannot.

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