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Naive Physics Reasoning: A Commitment to Substance-Based Conceptions

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A good deal of research has addressed the topic of naive physics knowledge, with a focus on the physics domain of classical mechanics. In particular, it has been proposed that novices enter into instruction with an existing, well-defined knowledge base that they have derived from their everyday experiences. Most relevant initial knowledge will be substance based, in the sense that it represents the novice's understanding of how material objects and other types of substances behave in the course of everyday life. Our position is that novices make every effort to assimilate new physics knowledge into their initial knowledge structures. Thus, abstract physics concepts will tend to be attributed with properties or behaviors of material substances. For example, force is considered by many novices to be a property of moving objects. Novices also appear to draw on their substance knowledge when they are asked to reason about other abstract concepts, such as light, heat, and electricity. Many researchers have explored naive conceptions of these concepts to the extent that a fairly broad view of the literature is now accessible. This article opens with a discussion of naive knowledge of material substances (including objects) and presents a broad theoretical framework

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called the *substance schema*, which is used throughout the article to refer to any generalized knowledge of material substances and objects. It must be noted that the term *schema* is used loosely in reference to any existing generalized knowledge; no arguments are presented concerning the actual “structure” of conceptual knowledge. Misconceptions of the concept of force are first briefly reviewed, followed by more extensive reviews of research concerned with naive conceptions of light, heat, and electricity. These reviews provide support for the claim that naive conceptions often reflect an underlying commitment to existing knowledge of material substances. The article closes with a discussion of the use of materialistic models by physicists and implications for instruction.

A large body of research has focused on the content and structure of the “initial” conceptual knowledge of physics novices. Although research on naive conceptions originated predominantly in the domain of physics (mechanics in particular), a large amount of work now also has been compiled that explores naive understanding of more abstract physics concepts, such as light, heat, and electricity. This research has been motivated by the fact that all of these concepts have proven to be notoriously difficult to learn in the science classroom. Students enter into instruction with firmly held conceptions that have shown themselves resistant to instruction—even when directly “confronted” by the curriculum. Chinn and Brewer (1993) discussed a spectrum of responses observed when novices receive evidence or instruction in conflict with their existing knowledge. The four concepts, *force, heat, light,* and *electric current,* have the common quality that they are all subject to noticeably “robust misconceptions.” Yet another degree of commonality is seen in the makeup of these naive conceptions: For all four of these concepts, novices seem inclined toward materialistic or “substance-based” conceptions. We provide a discussion of naive conceptions in these four topics to gain some understanding of why they should provide such a noticeable barrier to conceptual change.

Within the literature on mechanics reasoning, there is an ongoing debate about the structure of naive physics knowledge: To what degree does naive mechanics knowledge comprise a coherent “theory-like” structure, as opposed to a more phenomenologically based compilation of knowledge fragments? McCloskey (1983) suggested that “people develop on the basis of their everyday experience remarkably well-articulated naive theories of motion” (p. 301). It has been further argued by McCloskey and others that these naive theories resemble the impetus theory propounded by medieval philosophers (Halloun & Hestenes, 1985; McCloskey, 1983). Au (1994) suggested that even children as young as 3 years of age exhibit a well-defined, sophisticated, theory-like knowledge of substances. The difference in the context and amount of experience may govern the extent to which naive concepts are organized in a theory-like structure.

Apparently, however, there are some aspects of naive reasoning that suggest a more fragmented, less abstract knowledge structure. DiSessa (1988, 1993) pointed out that fewer than half of McCloskey’s (1983) physics novices demonstrated the impetus theory overtly, that novices are generally tentative in drawing conclusions from the impetus view, and that they sometimes overlook the impetus explanation in problems that afford a more convenient explanation. DiSessa (1988) advanced an alternative view of naive physics knowledge as consisting of "a fragmented collection of ideas, loosely connected and reinforcing, having none of the commitment or systematicity that one attributes to theories" (p. 50). Although they use a slightly different vocabulary than that of diSessa, several other researchers have adopted this "knowledge in pieces" view as well (e.g., Champagne, Klopfer, & Anderson, 1980; McDermott, 1984).

Although this article does not seek to provide evidence or weight to either side of this important debate, we do assume a certain degree of coherence (see Chi & Slotta, 1993). Our aim is to document a trend in the literature that naive conceptions of certain physics concepts are likely to resemble material objects or substances, or at least possess certain characteristics of material substances. Our thesis is that this general knowledge of material substances, their properties, and how they behave is drawn on as a source of conceptual information whenever the novice encounters a difficult new physics concept. Thus, novices may be inclined to think that concepts such as light, heat, and electricity are actual substances, behave like material objects, or are somehow the inherent properties of objects. With regard to the issue of knowledge coherence, we assume a generic knowledge structure (such as a schema) and acknowledge that conceptions of material substances may be more or less coherent within this assumed structure. Our *substance schema* is defined broadly to include all knowledge that is general to material substances but not necessarily to all material substances. That is, a person may have some knowledge that predominantly applies to fluids and other knowledge that characterizes the behavior of solid objects. Similarly, there is evidence that knowledge of material objects is distinct from knowledge of other types of substances,[1] such as fluids or conglomerations of objects, even in very young children. Thus, 2-year-olds are sensitive to the ontological distinction between an object (e.g., a statue) and the substance of which it is composed (e.g., rock; Soja, Carey, & Spelke, 1991), and preschoolers know that a material object (e.g., a wooden airplane) that is cut up into many pieces is no longer the same kind of object but that it is still the same kind of substance (Carey, 1991; Dickinson, 1987). "This means that even preschoolers appreciate the homogeneous structure of substances to some extent and differentiate principles that specify individualization and identity of substances from those that apply to objects" (Au, 1994, p. 73).

Although such developmental questions are important, they are peripheral to our basic qualitative hypothesis of a bias in naive thought toward conceptions that are

[1]Throughout this article, we use the term *material object* to refer to actual objects (e.g., a building, airplane, or wooden block) that have weight, surfaces, displace volume, and so forth. The term *material substance* is used to refer more broadly to any solid, liquid, or gas (e.g., wood, metal, or water).

grounded in existing knowledge of material substances. The substance schema is not proposed here as a formal knowledge structure and will not be developed in any level of sophistication. Rather, it is simply meant to capture the kind of knowledge that is built up about material objects and other types of substances, to test the hypothesis that naive physics conceptions are often attributed with this same knowledge.

DiSessa (1988, 1993) argued that the bulk of naive physics knowledge must be derived from everyday experiences with material substances. After countless observations and experiences with material substances and objects, a person will naturally begin to acquire an abstracted sense of the properties and behaviors of material objects and substance in general. Extending and applying experience from one domain to new situations seems to be a general mechanism of sense making: Young children use their knowledge about human beings to reason about other biological organisms (Carey, 1985). Similarly, physics novices may adopt knowledge structures consistent with an impetus theory because they often observe moving objects in the ordinary world to exhibit impetus-like behavior (due to the presence of invisible frictional and gravitational forces).

Our purpose in assuming the substance schema is to provide a framework in which to discuss the existing generalized knowledge of material substances, more or less independently of developmental or cognitive variables. This generalized knowledge appears to be used as a source of inference by physics novices as they reason about novel concepts like force, light, heat, and electricity. We propose a set of generalized attributes of material objects and substances that attempt to capture the basic qualities of this knowledge. These will include properties of material objects as well as behaviors and states of substances in general. Some attributes of objects may overlap with corresponding attributes of substances, such as location, motion, and friction. These attributes are not meant to be "normalized" (in the sense of being mutually independent of one another) so that there may be some degree of redundancy between them, as in the case of the attributes *pushable* and *containable* (discussed later). Where appropriate, we justify our descriptions of the properties by citing existing research from the literature on naive physics conceptions and developmental psychology. We note that the descriptions provided next constitute a fairly complete form of the substance schema. Some of these properties may develop during childhood, whereas others are already in place by infancy. Because most of the literature about naive physics conceptions is devoted to older children or even adults, we can assume that most of these properties are in place for the participants in the research studies reviewed.

THE SUBSTANCE SCHEMA: A GENERALIZED KNOWLEDGE OF MATERIAL SUBSTANCES

Our discussion of the substance schema includes the following properties, although it is important to state that we do not necessarily view these properties to be a comprehensive statement of substance knowledge, and we do not make any claims about the level of coherence or integration among them:

1. Substances are *pushable* (able to push and be pushed).
2. Substances are *frictional* (experience “drag” when moving in contact with some surface).
3. Substances are *containable* (able to be contained by something).
4. Substances are *consumable* (able to be “used up”).
5. Substances are *locational* (have a definite location).
6. Substances are *transitional* (able to move or be moved).
7. Substances are *stable* (do not spontaneously appear or disappear).
8. Substance can be of a *corpuscular nature* (have surface and volume).
9. Substances are *additive* (can be combined to increase mass and volume).
10. Substances are *inertial* (require a force to accelerate).
11. Substances are *gravity sensitive* (fall downward when dropped).

We briefly discuss each of these properties to show that they are learned early in development and persist throughout life as useful generalized knowledge of the attributes and behavior of material objects and substances.

Attributes 1 through 6 are basic recognition skills possessed even by preschool age (Piaget, 1930, 1973). Friction is recognized as resistance to motion, containability is a basic skill required as a prerequisite to the conservation experiments (containers of different shapes), consumability is often associated with conceptions of food, and location is recognized by infants as young as 4 months old (Streri & Spelke, 1988): From infancy, children experience pushing, being pushed, and motion. Piaget (1973) performed experiments concerning the dynamic concept of force. At all three of his proposed stages of development, he determined that children possessed the concept of push or pull. Johnson’s (1987) compulsive force schema describes an image schema that applies to a vast range of experiences and is central for meaning construction. Push and pull forces, and their relation to motion, are described in the next section, which deals with students’ ideas of forces. At this point, we simply observe that this is a very basic concept that appears early in development.

Substances Are Stable (Do Not Spontaneously Appear or Disappear)

There is also ample evidence of the belief in object permanence, even at a very young age (Spelke, 1990), although it is important to mention that belief in spontaneous disappearance may occur for young children when a substance is broken down into very small pieces. Children of ages 4, 6, and 10 years were told that a piece of Styrofoam was repeatedly cut in half until the piece obtained was so small that it could not be seen. All of the 4- and 6-year-olds and about one half of the 10-year-olds claimed the pieces would weigh nothing at all (Carey, 1991). Smith, Maclin, Grosslight, and Davis (1997) found that even some eighth-grade students persisted in this misconception. However, Au, Siddle, and Rollins (1993) found that children as young as 4 years old claim that sugar dissolved in water continues to exist, although it becomes invisible. Thus, the exact characterization of this belief remains a matter of developmental research, although there is ample evidence for the belief in many situations.

Substance Can Be of a Corpuscular Nature

There is a general agreement in the literature that children from the age of 10 years old frequently employ corpuscular notions of matter (Brook, Briggs, & Driver, 1984; Novick & Nusbaum, 1978; Pfundt, 1981). Still, this corpuscular notion is often coupled with a view of substance as continuous (Au, 1994), such that students deny the existence of space between particles, saying that space is filled in with dust, germs, air, other gases, and so forth (Osborne & Schollum, 1983). The corpuscular explanation is based on the projection of the macroscopic view (the object as a whole) to the microscopic view, such that the corpuscular elements are treated as small objects (Piaget & Inhelder, 1974).

Substances Are Additive

Additivity relates to the notion of conservation of matter as well as the stability property described before. Specifically, this is the idea that combining two or more quantities or volumes of a substance will result in a volume or quantity equal to their combined volumes or quantities. Children who do not yet demonstrate a conception of the conservation of matter may not exhibit any understandings of this property in their substance schema. After children have developed a sense of conservation, we can expect that additivity would be a strongly held belief with respect to the properties and behavior of substances.

Substances Are Inertial

Material objects and substances might have inertia, although this attribute may be more commonly applied to objects. Liquids or streams of liquid are not objects per se but can still have inertia. As we review next, such inertial properties of fluid-like substance may often be associated with naive conceptions of electric current and light.

Substances Are Gravity Sensitive (Fall Downward When Dropped)

Like the previous attribute, this one can be applied to substances in general as well as objects. Children acquire the concept of spilling and falling downward as early as infancy (Baillargeon, Spelke, & Wasserman, 1985; Piaget, 1930). Hence, weight and falling downward are parts of a fundamental conception of matter and will likely accompany any substance-like conceptions of physics topics.

Although this list of substance schema properties may be incomplete or redundant in some respects, it illustrates our main idea of what might comprise naive knowledge about the properties of material substances. Such fundamental knowledge of material objects is well documented by developmental research (e.g., Piaget, 1930; Spelke, 1990; Streri & Spelke, 1988) and is essential for comfortable existence in a world full of material objects. In this review, we explore how the substance schema (or its theoretical equivalent) may often be overextended to naive conceptions of certain science topics. Based on colloquial language or other cues, children or physics novices may infer that a topic like heat, light, or electric current is an actual substance, possessing all of the common properties of substances outlined previously.

SUBSTANCE-BASED MISCONCEPTIONS: AN OVERVIEW

When physics novices are asked to reason about events in which material objects experience collisions or constrained motion (e.g., billiard balls colliding on a table), the overriding result (Halloun & Hestenes, 1985) is that they are highly inconsistent and tentative in their explanations. Novices tend to explain forces and constraints as internal properties of the moving objects or as the intentional interference of some external agent (Law & Ki, 1987; Viennot, 1979). These observations suggest that the substance schema is used by novices as a source of inference for reasoning about such novel situations. Because children or physics novices have seldom perceived or experienced idealized motion (i.e., in the absence of frictional and gravitational forces), it is not surprising that their reasoning about such problems tends to include substance-like attributions. For example, when presented with a problem consisting of a massive block sliding on a frictional inclined plane, a physics novice might represent the problem in terms of his or her knowledge of real-world blocks and not the idealized block in the problem statement. This results in misconceptions of the block that include a “propensity to slow down,” as if attributes of the moving block are responsible for its gradual loss of speed. This article begins by reviewing the research on many such misconceptions of force, to show that they are consistent with the idea that participants draw on the substance schema as a source of conceptual knowledge.

Even more intriguing is the suggestion by numerous researchers that physics novices adopt substance-based conceptions when reasoning about abstract concepts such as light, heat, or electricity (e.g., C. Andersson & Karrqvist, 1983; Erickson & Tiberghien, 1985; Joshua & Dupin, 1987). It seems reasonable that, in the absence of any other relevant knowledge, novices would draw on their knowledge of material substances to arrive at explanations for these otherwise untenable concepts. This seems especially likely, given the materialistic language that is often used (in everyday language as well as in the science classroom) when referring to these concepts (e.g., "close the door, you're letting all the heat out," "throw some more light on things," etc.). We review the findings about misconceptions of each of these three concepts to show that novices attempt to conceptualize abstract ideas and events (e.g., electric current or the refraction of light) in terms of simple material substances and their interactions. Not only does this claim pave the way for a theoretical explanation of naive conceptions in abstract physics domains, but it also offers several empirical predictions as well as some interesting implications for instruction.

HOW THINGS CHANGE: THE DEPENDENCE OF NAIVE PHYSICS CONCEPTIONS ON THE DEVELOPMENT OF THE SUBSTANCE SCHEMA

Assuming that children draw on their existing substance schema as a source of physics conceptions, then the development of their understanding about material substances should influence the nature of their physics misconceptions. Indeed, there is ample evidence for such a dependency in our review. For example, the concept of light is often considered by children to be a substance, but what if their notion of substance undergoes changes? Then in principle, their substance-based misconception of light should follow suit. Indeed, children 8 to 10 years old have been observed (C. Andersson & Karrqvist, 1983) to view light as identical with its source, seemingly unable to conceptualize any view of light as existing in the airspace between the source and the target. At 12 to 13 years old, however, they are seen to conceptualize light as a stream of liquid or particles (Reiner, 1987). Perhaps this shift in their conception of light is correlated with an overarching transition in their understanding of corpuscular matter. A similar shift was identified for children's conceptualization of heat (Albert, 1978). Before the age of 9 or 10 years, children view heat as an inherent property of a material object. Afterward, the child is able to conceptualize heat as being independent of the object and adopts an alternative explanatory framework in which heat is seen as a separate entity (i.e., the "caloric" view) that flows in or out of a body.

Although such developmental transitions may provide insights into the development of conceptual knowledge of matter or substance, they do not in any way affect our hypothesis about the importance of the substance schema in physics reasoning. That is, if there is evidence that the substance schema develops, and we posit that it is a source of inference about abstract physics concepts, then we would expect to see naive conceptions exhibit corresponding developmental trends. We are encouraged by the evidence reviewed in this article, suggesting that there are indeed some corresponding developmental shifts in students' knowledge of substances and certain physics concepts.

Additional Issues

Because of the breadth of this review, there are some issues that should be mentioned at the outset. First, in reviewing such a wide range of misconception research, we are blurring the distinction between existing, well-instantiated naive conceptions (such as McCloskey's, 1983, observed "naive theories" of motion) and spontaneously generated (i.e., "first-encounter") reasoning events. One can imagine that both types of conceptions will be present in the various results discussed here because novices of varying degree participated in these studies (e.g., grade school children, high school prephysics, one semester of high school physics, one semester of university physics, etc.). Most likely, the older participants will have had more experience with these concepts and, thus, possess more well-defined misconceptions. Second, the developmental factor, discussed earlier, is apparent throughout this review but is not treated in any systematic way because it is sufficient for our purposes simply to note that development of misconceptions should correspond roughly with development of substance knowledge. Finally, the variety of methodologies employed within the studies reviewed certainly contributes some variance to the types of misconceptions observed. That is, 10-year-olds in one type of study (e.g., one that uses a particular type of observable) might exhibit a certain misconception of electric current, whereas the same age group may be found to possess entirely different sorts of conceptions of the same topic when a different type of task is used (e.g., problem solving in a microworld environment). Regardless, we argue that there exists a basic tendency for novices to view such concepts as material substances or as possessing attributes of material substances. Misconceptions may vary according to the surface features of the task (e.g., as diSessa, 1993, predicted) but should still adhere to the basic tendency.

SUBSTANCE-BASED CONCEPTIONS OF FORCE

Physics of Force

According to the theory of physics, all forces are due to interactions between material objects (French, 1971). The gravitational force arises between two objects because of their mass. The electromagnetic force results from the interaction of electrically charged objects. Finally, the strong and weak nuclear forces[2] govern the interaction of subatomic particles in close proximity to one another (approximately 10^{-15} m). With these four basic forces,[3] physicists are able to account for virtually all material interactions. A final force classification, the *contact force,* is used by physicists to describe the observed forces between ordinary material objects in mechanical contact with one another. The contact force is actually a manifestation of the lower level electromagnetic interactions between the very large number of atoms that make up ordinary material objects and is, therefore, not a distinct type of force. However, in the domain of mechanics, the contact force is used more frequently than any of the others listed. Different contact forces include the spring force, the tension force, friction forces, and the force of one object that pushes against another (e.g., the normal force exerted against an object by a supporting table top).

Forces between material objects are observed to cause changes in their respective velocities. For example, the gravitational force between the earth and a material object tossed into the air will cause that object to move (fall) more and more quickly toward the center of the earth,[4] while the earth itself will accelerate (albeit imperceptibly) toward the falling object. The falling object and the earth's center will continue to accelerate toward one another until some counterforce impedes their progress (e.g., air resistance or eventually the surface of the earth itself). Indeed, acceleration can serve as an alternative source of definition for the concept of force. Isaac Newton (1642–1727) was the first to clearly articulate the relation between force and acceleration. Newton's first law, set forth in his *Principia Mathematica* (1687/1952) states that "every body perseveres in its state of rest, or of uniform motion in a straight line, unless it is compelled to change that state by forces impressed upon it." In his second law, Newton established the famous equation, $F = m \times a$, where F represents the vector sum of all forces acting on an object (whose mass is represented by m), and a represents the resulting acceleration of the object.

Thus, in physics, force is seen as a *process*[5] of interaction involving two or more material objects in which these objects are sped up, slowed down, or redi-

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[2]The distinction is drawn in physics between "strong" and "weak" nuclear forces, depending on the exact nature of the subatomic interactions involved.

[3]There is currently some debate as to the existence of an additional force, referred to as the *fifth force,* which would depend on the baryon number, or hypercharge, of the interacting particles.

[4]In this classic problem, the earth must be treated as a single point located at the earth's center of mass. It is this point which accelerates toward the falling object.

[5]We have argued (e.g., Chi & Slotta, 1993; Slotta, Chi, & Joram, 1995) that many difficult physics concepts are actually processes—not substances—and that this ontological difference between expert and novice conceptions is responsible for the notorious difficulty experienced by novices in moving from their initial conceptions to a more formal physics view. Thus, force can be seen as a process of interaction between two objects, heat can be seen as a process of energy transfer from an object to its surroundings, light can be seen as a process of electromagnetic energy propagation, and electric current can be seen as a process in which electrons move under the influence of electromagnetic forces. All of these concepts are misconceived by novices as actual material substances, or at least as possessing the attributes of substances.

rected.[6] This conception of force as a process is qualitatively distinct from any substance-based view of force (e.g., as a property of an object). Chi (1992; Chi, Slotta, & deLeeuw, 1994) characterized the difference between process-based conceptions (typical of many physics concepts) and substance-based conceptions (typical of many naive conceptions) as an *ontological* one, which may be responsible for the difficulties in learning such concepts.

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Naive Conceptions of Force

There has been a considerable amount of research into the nature of naive conceptions of force. Initial studies (e.g., Clement, 1982; Halloun & Hestenes, 1985; McCloskey, Caramazza, & Green, 1980) have shown that novices possess well-instantiated conceptions of force and that these naive ideas are persistent throughout instruction. In the past decade, a flurry of research has sought to discover the precise nature of these naive conceptions. Pfundt and Duit (1991) provided a list of nearly 2,000 published articles (dating between 1979 and 1987) concerned solely with student misconceptions in mechanics. In all of this research, it is clear that physics novices do not conceive of force as a process of interaction between two material objects. Rather, the most commonly reported naive conception is that force is a property of a single moving object, consistent with the medieval impetus theory (McCloskey, 1983; Viennot, 1979).

There are two ways in which novices predominantly associate a physics concept with some attribute of a substance: The concept itself can be thought of as an actual material substance; otherwise, the concept could be thought of as a property of a material substance. In the case of the impetus-like conception of force, for example, students often believe (Law & Ki, 1987) that the "impetus" object exerts a force on another material object; thus, providing it with the potential to exert a force on a third object. This is consistent either with the belief that the impetus-force is an extensive property of the first object, which may be transferred to the second, and then onto the third, or with the view that the impetus-force is an actual object or substance that is carried along by the first object and then transferred over to the second. These two notions are very clearly based on the idea that a force is not a process of interaction but is instead either a substance or the property of a

[6]An object is said to undergo some acceleration if either the magnitude or direction of its velocity changes. Thus, an object can accelerate even if it moves at a constant speed.

substance. In the following sections, we briefly review the literature on misconceptions of force to provide evidence of substance-based misconceptions.

An internal supply of force. Viennot (1979) showed that a novice's conception of the force acting on a material object depends on the object's velocity. She proposed the notion of a "supply force" as "the force which keeps (the object) in motion" (p. 208) and compared this idea with the medieval notion of impetus. Clement (1982) provided additional evidence of this naive conception that "motion implies a force" (p. 67). He reported that 88% of his participants (first-semester engineering students with a high school physics background) believed that a coin tossed into the air will possess an upward force whose magnitude is greater than that of the downward gravitational force. McCloskey (1983) elaborated on these ideas, claiming that physics novices maintain a basic impetus theory consisting of two fundamental beliefs: that all moving objects possess an internal force (impetus) and that this impetus gradually dissipates over time, causing the object to slow down and eventually come to rest. Many other researchers have documented the existence of this naive conception, including Champagne et al. (1980), Minstrell (1982), Halloun and Hestenes (1985), and Law and Ki (1987). It is, thus, fairly conclusive that novices associate movement of objects with force and often conceptualize this force as a property of the moving object. This conception of force serves as a good demonstration of the underlying object-based force schema in naive thought. Force is thought of not as a field potential act independent of material objects but as some act of the object itself.

Gravity as an innate property of material objects and substances. Gravity presents a problem to the impetus theory because it appears to impart impetus to a material object from a distance (i.e., without involving any contact between the object and some external agent). Unequipped with the concept of a gravitational field, novices tend to explain this unique supply of force by assuming an innate, inexhaustible internal property called *weight.* Every object will naturally fall down under the force of its own weight (Driver, 1985; Mayer, 1987; Vincentini-Missoni, 1981). Thus, physics novices think of gravity, one of the four basic fields in nature, as the potential of all material objects to fall. One might expect this basic thought to play a very important role in a novice's substance schema. Because the "action at a distance" quality of the gravitational force is unavailable to them, novices may attempt more complicated conceptions of gravity and weight. Typically, such explanations involve contact forces between the falling object and molecules of air. Vincentini-Missoni (1981) reported that adult novices explain the fact that an object will fall if dropped by appealing to the contact of air pressure. Similar results are reported by Watts and Zylbersztain (1981), Gunstone and Watts (1985), and Driver (1985), whose students believed that there was no gravity in outer space due to the lack of air pressure.

The available evidence concerning naive conceptions of force supports our hypothesis that physics novices tend to associate abstract concepts with a well-instantiated substance schema. When queried about the forces affecting an object in motion (e.g., McCloskey, 1983; Viennot, 1979), novices respond by confounding force with velocity, thereby attributing the object with an attribute of "having force"—a status similar to the medieval concept of impetus. Physics novices, unfamiliar with the conceptualization of force offered by the physics theory, try to make sense of the concept by appealing to their reliable understanding of the material world—namely, to the substance schema. In our description of the substance schema, we have included the item "material objects are gravity sensitive." This is meant to reinforce the idea that the phenomenon of weight is seen as inherent in every object. It is clear from the research described here that novices have a definite conception of weight in their substance schema that has nothing to do with the gravitational field as defined by physics. The research in naive conceptions of mechanics has, thus, informed our understanding of the substance schema while supporting the idea that novices are guided in their reasoning by an underlying commitment to their knowledge of substances. We now explore the hypothesis that novices also rely on the substance schema in conceptualizing other abstract physics concepts, such as light, heat, and electricity.

MATERIALIZATION OF LIGHT

Physics of Light

In the formal theory of physics, light is viewed as something of a paradox. This is not to say that physicists are unsure of their theoretical description of light. Rather, there are several distinct levels of description for light, each with its own formalism and existing more or less independently of the others.[7] In classical electromagnetic theory, light is described by Maxwell's equations and is conceptualized as a traveling electromagnetic wave, whose constant speed, *c*, is the "speed of light."[8] This theoretical account is perfectly adequate for almost every "real-world" application or experience of light, including simple optics problems, illumination of buildings, most telescopes and microscopes, and television and radio broadcasting. Like Newtonian mechanics, however, the classical account of light has its limitations

[7]It is important to note that, under the modern quantum electrodynamic (QED) theory and field theory, light is not paradoxical. The wave-like and the particle-like nature of light are both understood and comprehensively described by this highest level of physics theory.

[8]The constant *c* is the speed of the light wave. If the wave is traveling in a vacuum, this constant equals approximately 3 × 108 m/sec. Otherwise, *c* is a slightly smaller number.

and was eventually surpassed by more advanced theories, such as quantum electrodynamic (QED) and field theory. These modern theories offer an even more exotic conception in which light consists of massless "particles" that are fundamentally wave-like in nature, such that their behavior is somewhat particle-like and somewhat wave-like. A particle of light, or photon, is basically a "wave packet." The two representations are absolutely coherent and are not considered as different conceptualizations. Physicists think of light in both ways, depending on the context, moving back and forth between the two representations.

Naive Conceptions of Light

Guesne (1985) showed that physics novices have difficulty thinking about light. In one study, 12- to 15-year-olds were able to recognize the connection between a particular light source and a spot of light on the wall but were unable to conceive of light as existing in the intermediary space. This finding does not suggest a naive conception of light as an actual substance that can move. To identify light with either its source or its target is common in our everyday experience, in which we rarely have any cause to consider the invisible space in between. However, once physics novices have been persuaded to think of light as having an existence independent of its source or target, they tend to adopt a materialistic conception. For example, C. Andersson and Karrqvist (1983) showed that, when trying to explain the phenomenon of sight, participants make an explicit appeal to the existence of molecules "in between" the book and the eye. Reiner (1987) also found evidence that novices explain sight as the result of moving particles of light. Depending on the circumstances, novices will adopt different materialistic conceptions of light. Reiner observed that a large proportion of her participants chose to compare light to a stream of fluid. Guesne, Sere, and Tieberghien (1983) also recorded evidence of this fluid-like conception.

Several studies have demonstrated that materialistic conceptions of light are persistent through adulthood—in some cases even when individuals have received a substantial amount of physics instruction. Smith (1987) reported a study in which 6 out of 10 elementary school teachers demonstrated a materialistic commitment in their explanation of light and shadows. Similarly, Reiner (1987) found that high school physics instructors explained both the rotation of a radiometer and lightning's disturbance of television reception by appealing to a particle model of light in which moving photons actually collided with the radiometer and the television antenna and thereby exerted a force on it. The photon is conceived as an object that exerts force just like the moving objects discussed earlier that are considered impetus-objects.

The next several sections explore some basic characteristics that appear consistently in studies of naive conceptions about light: Light flows and can be at rest;

light mixes as if it were a liquid; light creates friction on contact; and light, color, and shadows exist only in an object. The last item in this list serves to examine an alternative application of the substance schema in which novices conceptualize light not as an independent substance but as an intrinsic property of an object, like its weight. Although young children consider light a property of objects (as opposed to a substance), novices of all ages think of colors and shadows as intrinsic properties of objects. The following characteristics reflect our synthesis of the literature in terms of the substance schema.

Light flows and can be at rest. As mentioned previously, many novices conceive of light as a fluid. Jung (1981) found that 12- to 15-year-old students believed that if a ray of light were aimed at a mirror, a spot of light would be seen on the surface of the mirror. Even when reminded that the mirror would reflect the light beam, students maintained that a small bright spot would appear on its surface. This result is consistent with the conception of light as a fluid: Even if some idealized stream of water were reflected perfectly from a surface, the point of reflection would still be wet. Guesne (1985) reported a similar result when participants were asked what would happen when a flashlight was aimed at either a white piece of paper or a mirror. The majority of participants responded that the light beam would be reflected from the mirror but would come to rest on the paper. That some of the light is believed to remain on the reflecting surface in Jung's study, and the white paper in Guesne's study, reveals another characteristic of the "fluid model": that light can be at rest. It is not surprising that children and adult novices would attribute this property (able to be stationary) to light, given an underlying materialistic commitment. It follows directly from the substance schema that a material can come to rest.

Light mixes as if it were a liquid. Everyday experience has taught us that when two paints of different color are mixed together, the result will be a paint whose color is "in between" that of the two originals. For instance, mixing a red and a blue paint together will typically result in some shade of purple. Experience has also shown that adding even a small amount of a dark-colored paint to a bright-colored one will result in a darkening of the original bright color. The rules of thumb for mixing different colors of light, however, are quite the opposite. A spot of red light on the wall, mixed together with a spot of green light, will result not in a brown spot, but in a yellow one. This result violates both of the paint mixing rules described, for not only is the resulting color far from the predicted brown, it is also a brighter color than either red or green. If physics novices really do think of light as a fluid, then they would naturally think of colored light as a colored fluid. This leads directly to the following empirical prediction: When asked questions about simple mixtures of colored light, novices will make errors according to the paint mixing rules. This prediction has now been tested in numerous studies with clearly positive results.

C. Andersson and Karrqvist (1982) asked students to explain the effect of colored filters on a white flashlight beam. Although they reported six categories of explanation, a rough classification of these categories reveals that the majority (more than 70%) of participants employed a "paint-mixing" explanation to account for the effects of the filters. Slotta, Chi, and Joram (1995) replicated this finding in one of their stimulus items. Similarly, Reiner (1987) found that 95% of her high school students believed that a red beam of light viewed through a blue filter would appear as a purple beam. Even when they were confronted with contradicting evidence (the beam actually appears black, as no red light may pass through a blue filter), they insisted that the blue filter was just too dark and "dominated" the red beam. When asked to justify their reasoning, participants frequently appealed to analogies concerning the mixture of red and blue liquids, thus overtly indicating the nature of their misconceptions. In another study, Olivieri, Torosantucci, and Vicentini (1988) used shadows from colored light sources to stimulate explanations about light phenomena. They interviewed adults (including math and science educators) and reported that more than 95% of the 37 participants referred to the mixing of paints for the explanation of light behavior. These results suggest that physics novices may employ a "fluid-like" conception of light when trying to predict or explain the mixture of colored light sources.

Light creates friction upon contact. To explain the fact that light cannot penetrate opaque materials, novices often appeal to the idea of some direct physical contact between materialistic light particles (or fluid) and the opaque substance. Similar explanations are used to account for the fact that light becomes more faint with distance as it travels through the air: "Friction" from the air slows down or stops some of the light until, finally, none of it remains. Such materialistic accounts of the interaction between light and matter have been observed by Stead and Osborne (1979), Guesne (1985), Beuwens (1987), and Reiner (1987). For instance, when participants in Reiner's study were asked why a beam of white light heats up a cup of black coffee, 55% explained that friction between the particles of light and the coffee molecules is the cause of the coffee's temperature increase.

Although in some cases it may seem as if the interactions between light and matter are of a mechanical nature (e.g., when light heats up a black surface or turns the vanes of a radiometer), these are actually complicated electromagnetic phenomena. Hence, although materialistic explanations are sometimes a fair approximation of the actual scientific account, it is clear that they are a source of misconception. For example, Stead and Osborne (1979) reported that novices think light travels farther at night than it does in the daylight, presumably because the greater quantity of light in the air during daylight hours will be a greater source of friction.

Light, color, and shadows as something inherent of an object. As described earlier, novices have difficulty conceiving of light as existing independently of its source. Guesne (1985) reported that children do not believe that light can move, "because light is the sun, and the sun cannot move" (p. 14). C. Andersson and Karrqvist (1983), Smith (1987), and Apelman (1984) all reported similar findings. As a result of this unwillingness to think of light apart from its source, novices also tend to assume that several of the effects of light—brightness, color, and shadows—are actually the illuminated material substance. For example, Apelman and Smith both observed that students explain color as being inherent to an object (e.g., a red book), rather than the result of its interaction with external entities such as "light" and vision.[9]

Although shadows are really nothing more than the occlusion of light by an object, they are often interpreted by novices as being an intrinsic property of the object. Piaget (1930) was perhaps the first to make this observation, with more recent studies reported by Apelman (1984), Guesne (1985), and Feher and Rice (1986). It is interesting that, whereas physicists interpret shadows and darkness as the absence of something, novices may well interpret them as the presence of something. In Feher and Rice' study, nearly 50% of the participants believed that shadows exist in the darkness. Some participants thought that light was necessary only to illuminate the shadow (as if it were just another object), whereas others believed that light actually caused the shadow's visibility (e.g., by heating it up). Still, in both cases participants believed that shadows actually have an existence of their own. In Apelman's study, five out of seven elementary school teachers believed that a dog would still have a shadow when it walked into the full shadow of a house. So physics novices of all ages tend to conceptualize shadows not as the simple absence of light, but as materialistic properties of illuminated objects.

MATERIALIZATION OF HEAT

Physics of Heat

The term *heat* is not used very often in physics, mainly because the general term *energy* has earned itself a more prominent place in the physics vocabulary. Heat refers to the transfer—usually the release—of energy from one object to another (or to the atmosphere). Physicists find it more convenient to talk about "how much energy" is being released or absorbed by a substance than "how much heat." This energy exists within a substance in the form of vibrating molecules and is called the internal

[9]Indeed, the physical makeup of an object and the nature of the impinging light are equally responsible for the object's color. Hence, all light being equal (i.e., the normal "white light" of sunshine and lightbulbs), color can be safely interpreted as a property of the object.

kinetic energy.[10] The more internal kinetic energy an object has, the hotter the object will feel to the touch, and the more "heat" may be released when the object comes into contact with a cooler object. The related term *temperature* is used to quantify the kinetic energy within a substance.

The relation between temperature and heat was not always clearly understood by physicists, just as it is not clearly understood by physics novices today. At the beginning of the 19th century, the dominant theory of heat was that it was an indestructible substance (called caloric) that flowed from a hot body (rich in caloric) to a cold body (with less caloric). The temperature of a body was, thus, a measure of how much caloric it contained. Using this idea of a flowing substance, early physicists were able to account for many thermal phenomena (e.g., the expansion of a body with increasing temperature was caused by the influx of caloric). This theory was readily overthrown, in part by the observation made by Count Rumford that physical work on a substance could also raise its temperature, thus implying that caloric could be created (in violation of the theory).

Naive Conceptions of Heat

Physics novices also appear to consider heat and temperature as distinct material substances. Several researchers (e.g., Erickson, 1980; Guesne, 1985; Rogan, 1988; Tiberghien, 1979) examined these naive conceptions and seem to agree that novices possess a materialistic view of heat that resembles the early caloric theory. One study, performed by Fuchs (1987), serves to reflect the degree to which this materialistic commitment is resistant to instruction. Fuchs asked 31 advanced engineering students (juniors and seniors), all of whom had studied thermodynamics, to write an essay about their conception of heat. He summarized the students view of heat as "a medium which is stored in bodies, and which can flow from one body to another" (p. 161).

Erickson (1980) performed perhaps the most extensive examination of children's beliefs about heat and temperature. He tested a fairly large population of students using a testing instrument called a "conceptual profile inventory." It consisted of a series of three explanatory statements about actual physical demonstrations, accompanied by bipolar scales to measure students' preference for each explanation. The three explanations used by Erickson were drawn from (a) the veridical kinetic theory of temperature and heat, (b) the caloric viewpoint, and (c) a "children's viewpoint" that had been derived from clinical interviews with young children. Participants in this study exhibited three basic response profiles, which differed in the extent to which they agreed with the kinetic or the children's view-

[10]In the case of a fluid or gas, the molecules also have kinetic energy due to their rotation and their overall movement (translation) through the substance.

point but were unanimous in their acceptance of the caloric explanations. These results provide evidence that there is indeed a tendency in naive thought to conceptualize heat and temperature as a caloric substance.

As in the case of light, naive conceptions of heat are not always self-consistent. The overall flavor of the research is that physics novices tend to think of heat as a material substance that behaves in accordance with the substance schema as it was defined previously. As with the topic of light, the research is presented in terms of several properties of materialistic heat that reflect the substance-like nature of these naive conceptions. Also, because there has been some interesting work concerning the topic of “cold” (the opposite of “heat,” as in “don’t let the cold in”), this is included in the discussion. The categories chosen reflect the focus of research on misconceptions of heat: Heat and cold are properties of an object, cold is not the absence of heat but rather a distinct substance, heat and cold flow and have definite physical location, and heat and cold accumulate and can be contained.

Heat and cold are inherent properties of objects. As in the conception of light, it is difficult for young children to conceive of heat as existing independently of the object. Albert (1978) examined the development of the concept of heat and found that only after the age of 6 years could children differentiate between the concept of a hot object and that of an object that is the source of heat. Only after the age of 9 years were children able to conceive of heat as an abstract concept. Guesne (1980) found the same basic tendency in the development of children’s conception of cold. Thus, heat and cold are viewed as hot objects and cold objects. Again, this seems a natural consequence of the fact that most ordinary experiences with temperature and heat consist of encounters with objects that are either hot or cold (e.g., “the sun is hot” or “the ice is cold”; furthermore, ice is always considered cold—it represents cold). In this way, misconceptions can be seen to generally derive from the child’s phenomenological experience of the concept in everyday life (diSessa, 1988). Such experiences are highly consistent with the view of heat as a property.

Although Erickson (1980), Tiberghien (1979), and Engel (1982) all found evidence of this “children’s viewpoint” in the reasoning of much older students (fifth, seventh, and ninth graders, or 13-year-olds and 12- through 16-year-olds, respectively), the overriding observation in the research is that a shift occurs in children’s conception of heat at approximately 9 years of age. Before this age, heat is viewed as inherent of an object. Once the novice has recognized heat as being independent of an object, however, he or she adopts an alternative explanatory framework and conceptualizes heat as a sort of caloric. Once again, there appear to be two distinct mechanisms of materialization: one in which the abstract entity is conceptualized as inherent in an object and the other in which the abstract entity is itself considered to be a material substance. Of these two mechanisms, the latter is more sophisticated and is generally held by older novices.

Cold is not the absence of heat but rather a distinct substance. The relation between heat (or, more appropriately here, "hot") and cold is similar to that of light and shadows. Indeed, cold is simply the absence of heat (really, "temperature"), just as shadows are simply the absence of light. As in their conception of shadows, novices tend to conceive of cold as an independent materialistic entity. This conclusion is supported by the results of Engel, Clough, and Driver (1986), who found a significant difference in the pattern of responses given by students to questions concerning the conduction of heat as compared to the conduction of coldness. Additional evidence of a distinct conception of cold might be derived from studies performed by Erickson (1979), Tiberghien (1979), and others—all of which show evidence that novices reason about a substance called cold when considering cold things (e.g., ice cubes, cold handlebars on a bicycle, etc.). An example from Tiberghien (1979) might be useful in demonstrating this type of reasoning. Considering a cold metal substance, one participant offered the following explanation: "Because the cold lasts longer, it evaporates less, [the metal] is harder, it's more solid." The observation that novices attribute many of the same properties to cold that they also apply to heat suggests that it is conceptualized as a distinct material substance.

Heat and cold flow and have definite physical location. The substances called heat and cold by novices are indeed materialistic in that they exist at a definite location, travel through space, arrive at a substance, and have an effect on it. In describing the flow of heat through a metal bar, for instance, one participant in a study by Reiner (1982) explained, "The heat did not arrive yet to this end. It takes some time to arrive … heat cannot heat from far away, it has to touch it (the object), to be in it and touch it from all directions." In earlier studies, Triplett (1973) and Erickson (1979) observed similar explanations of this phenomenon. Tiberghien (1979) quoted one of her participants: "If you put an ice cube inside it, the cold scatters all over the surface … so it will cool down." This suggests that novices also have a conception of cold as a flowing substance. From his analysis of interviews with 12-year-old students, Erickson (1979) compiled the following descriptions of naive ideas about how heat actually flows through different objects: A large rod heats up faster than a small rod because the large rod has more air spaces for the heat to travel through; wax melts quickly because it is a soft material and, therefore, is easier for the heat to go through; metal cubes get hotter than wooden or sugar cubes because it is more difficult for the air to go inside the hard metal cubes to cool them down.

Heat and cold accumulate and can be contained. The discussion of heat flow in the previous section suggests that physics novices often refer to the accumulation of heat or cold when explaining thermal phenomena. Tiberghien (1979), for instance, reported the following participant's explanation of the difference in temperature between a metal and plastic spoon, both of which are submerged in a single hot water bath: "This metal spoon holds the heat, or even the cold, it keeps it." Presumably, this participant believes that heat will accumulate in the metal spoon to a greater extent than in the plastic spoon. Several researchers have reported a similar naive belief in relation to the phenomenon of temperature increase. According to Erickson (1979), novices associate higher temperatures with greater accumulations of heat. Indeed, B. Andersson (1980) reported that 40% of his participants (sixth-grade Swedish students) believe that a pan of boiling water will increase in temperature if allowed to continue boiling for 5 min,[11] which is consistent with the notion of accumulating heat.

Even more intriguing is the result obtained by Stavy and Strauss (1983) in which a large majority of participants believed that the result of combining two volumes of water, each one at a temperature of 10º C, would be a volume whose temperature is 20º C. Stavy and Strauss suggested that participants think of the temperature as an intensive property (like mass or volume). Although this conclusion would provide dramatic support for the "heat is a property" view discussed earlier, an alternative interpretation should be considered. Perhaps the novices are simply imagining that in combining the two smaller volumes, the total amount of the heat substance (caloric) also doubles. Because heat itself is viewed as a distinct material substance, there will be twice as much of it in the final mixture, and so the temperature of the final volume will double as well. Of course, this interpretation requires the further assumption that temperature and heat are used interchangeably (Wiser & Carey, 1983). Indeed, this is an error that is very common and follows readily from the materialistic conception of heat.

MATERIALIZATION OF ELECTRICITY

Physics of Electricity

The electromagnetic field is one of the four fundamental fields in nature, according to the physical theory (French, 1971). Electric charge is likewise one of the basic properties of matter (cf. mass and volume). Only objects with some net electric charge may experience electromagnetic forces. Most objects in our everyday expe-

[11]The temperature of boiling water will never increase; it is a constant 100º C.

rience (e.g., desks, chairs, coffee cups, and even most electrical appliances) have a negligible net electric charge, but in the world of physics there are many circumstances in which objects have significant electric charges. The final necessary ingredients are the electric and magnetic fields.[12] These are *force fields* that extend infinitely away from their source, becoming ever weaker at farther distances. Charged objects in an electric or magnetic field will experience an electromagnetic force and will move under this force unless restrained by some opposing force. This discussion, although greatly simplified, serves as an outline for most of the necessary theoretical concepts underlying the applied theory of electrical circuits.

We briefly define the three basic concepts encountered by novices in most of the studies that are reviewed in the sections to follow: *voltage*, *current*, and *resistance*. Voltage, most often associated with a battery (e.g., a 12-V battery) can be thought of as the source of an electric field. When a battery is present, there is an electric field directed from one of its terminals to the other. When a wire is connected between the battery's two terminals, charged particles (called *electrons*) within the metal wire will experience an electromagnetic force due to the voltage, resulting in a net migration of electrons along the wire.[13] This flow of electrons is known as an electrical current. If a wire is placed so as to directly link the two terminals of a battery, this is known as a *circuit* because an electrical current will be free to flow in a continuous fashion. However, such a trivial circuit would not be useful, would waste the battery's energy, and would have serious practical drawbacks.[14] Normally, one or more electrical devices would be included within the path of the circuit so as to make the current do some useful work on its way from one battery terminal to the other. For example, a lightbulb and a switch might be placed in the circuit. When the switch was open (turned off) no current would flow in the circuit. When the switch was closed (turned on) the current would flow through the bulb and would illuminate it. Devices in the circuit provide electrical resistance, which effectively reduces the current flow.

One can imagine a circuit with such great resistance that the current barely flows through it and is unable to perform the desired work (e.g., turn a motor or illuminate a lamp). One simple way to produce more current in such a circuit is to

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[12]The electric and magnetic fields are actually just a mathematical formalism and have no physical reality in and of themselves. They are, however, invaluable in their capacity to completely describe the interaction between a charged particle and its environment. In other words, if one knows the field strength at all points in space and as a function of time, then one can completely describe the force that would be experienced by an (arbitrary) electric charge placed in the field.

[13]Electrons will typically have some large, though randomly directed, velocity within the metal wire even in the absence of a voltage. The effect of the voltage, then, is to simply add a small, systematic velocity to the existing random velocities of the electrons in the wire.

[14]The electric field from the battery might be so strong that it will attempt to force too large an electrical current around the circuit, and the wire will literally melt. Electrical devices placed within the path of the current, thus providing resistance, will effectively avert such catastrophes.

get a higher voltage battery. The fundamental law that governs such relations in electrical circuits, Ohm's Law, is expressed by the mathematical relation $V = I \times R$, where V stands for voltage, I stands for electrical current, and R stands for resistance. This law means that in a circuit whose resistance is R, I will vary directly with the V. Doubling the voltage will double the current and so on. A correct understanding of Ohm's Law will provide sufficient knowledge to solve many simple circuit problems. Notice that, although there is substantial materialistic language used within the definitions given here, particularly with respect to electrical current, none of the three basic concepts are actual material substances. That is, electrical current cannot be described by the substance schema as outlined at the beginning of this article.

Naive Conceptions of Electricity

To the mind of a prehistoric person, any electrical phenomenon (e.g., the illumination of an electric bulb, the spinning of an electric motor, etc.) would have been perceived as magic. Of course, this is by no means true of Western novices. From birth, we are constantly surrounded by electronic devices and soon come to take their behavior for granted. Even if we have never before used or seen a particular electronic gadget, we immediately begin searching out its switches and controls. Thus, a person might possess well-defined routines and knowledge structures for the use of electrical devices even though he or she might never have considered the underlying physical realities involved. When asked to describe electrical current or voltage, a physics novice may never have really thought about it before.

When 8th- and 10th-grade high school students were asked to classify current as an event, a substance, or a property, the majority responded that it was a substance (Jung, 1985). It is also interesting to note that more 10th graders (68%) than 8th graders (50%) gave this response. Hence, the conception of electrical current as a material substance does not appear to diminish with age. An important distinction must also be made between the notion of a substance (e.g., a fluid) and the notion of a moving substance. When considering a stream of water, for example, the current does not really flow; it is more correct to say that the water flows, and the current is the process of its flowing. From the body of research reported next, it appears that novices tend to think of current more as an actual substance than as the movement of some substance. This result has been widely reported (Cohen, Eylon, & Ganiel, 1983; Cosgrove & Osborne, 1985; Duit, 1986; Fredette & Lockhead, 1980; Shipstone, 1984), and there is basic agreement in the literature concerning the following naive conception of simple electrical circuits: There is a source, called the battery, of some substance, called the current, which is consumed by the device (e.g., the lamp) in the circuit.

Naive conceptions of voltage are not as clearly defined as those of current. Everyday notions of voltage are related to the physical size of the battery or sometimes to the mysterious number associated with batteries or electrical outlets. Unlike the flow of current, which does have materialistic associations in everyday life (e.g., water in pipes), the concept of voltage has no apparent associates in the material world. Results from the research suggest that, when novices are forced to think about the concept of voltage, they attempt to incorporate it into their existing materialistic interpretation of current. Hence, voltage is often thought of as a property of the current, such as the force that drives it. Rhoneck (1986) found evidence of a naive belief that voltage from a drained battery “has less force” because it has lost most of its current. Thus, the conception of voltage as the force behind electrical current seems to stem from the naive belief that current is stored in the battery.

In the following sections, a wide array of research is reviewed and organized according to several properties that seem to characterize the naive conceptions of electricity. It is our aim in this article to show that naive conceptions are strongly influenced by an underlying materialistic commitment that relies primarily on the novice’s everyday knowledge of material substances (i.e., the substance schema). In the domain of electricity, the focus is on the concepts of electrical current and voltage according to the following properties: Current flows and creates friction on contact, current can be stored and consumed, voltage is a substance, and voltage is a property of current or the battery. Thus, to the extent that naive conceptions of electricity adhere to these properties, we suggest that they are indeed the products of an underlying materialistic commitment.

Current flows and creates friction on contact. Although the notion of a flowing substance called current is practically universal in naive conceptions of electricity, there do seem to be several distinct ideas or models about how electrical current actually moves through a simple circuit. Because to some extent these ideas reflect differences in amount of instruction, it is not completely clear which, if any, should be considered “the most naive.” We therefore simply list them in approximate order of proximity to the “correct view” and make the observation that to some extent all of the models exhibit a materialization of current as a distinct substance, not as a property of the conductors and resistors in the circuit.

1. The unipolar model (e.g., Joshua & Dupin, 1987): There is no current in the returning path. The current stored in the battery needs only one wire to get to the lamp. Some novices state that one wire will be sufficient, whereas others regard the return wire as necessary but only in a passive sense (e.g., to get the lamp ignited).
2. The clashing current model (e.g., Steinberg, 1987): Current flows outward from both terminals of the battery. The two streams of current “clash” together at the lamp, causing it to illuminate.

3. The attenuation model (e.g., Gott, 1985): Current flows from one terminal of the battery, through the lamp, and arrives at the other terminal. As it passes through the lamp, some of the current is consumed or "used up" and hence it is attenuated when it emerges from the lamp. If two lamps are placed in the circuit, the second will not shine as brightly as the first because the first will attenuate the current.

Which of these models is used by a particular novice depends to some extent on the superficial context of the circuit (Duit, 1986; Karrqvist, 1985). Although there is a tendency for the student to use more advanced models with increased level of instruction, there can be remarkable "fallbacks" to more primitive models when the specific structure of the circuit "invites" their use (McDermott & van Zee, 1984).

Because current is seen as a distinct substance flowing through other substances (the wires, resistors, and devices), there is some tendency for novices to think that the current experiences a frictional force as it flows through the circuit. When Steinberg (1987) asked students to explain the heating up of resistors[15] placed in the circuit, many of them appealed to the idea of friction in their response. Another effect of this frictional aspect of materialized current is suggested by Gott (1985). When participants were shown a circuit with two lamps connected in series (one after the other), they thought that the second lamp would be dimmer than the first. Although student explanations were not analyzed, this result is consistent with the attenuation model described previously. The pattern of student responses suggests that current is thought of as an actual material substance that flows through the wire and experiences a frictional force from the wire and from any resistors it encounters along its way. In the next section, additional qualities of such naive conceptions are discussed, particularly the notion that it is consumed by electrical devices.

Current can be stored and consumed. Naive conceptions of electrical current include the idea that current can be stored. Batteries, of course, are the most likely candidates for the storage location because they have both the appearance and properties of a container. Indeed, McDermott and Shaffer (1992) provided evidence that novices think of batteries as fixed capacity storage vessels for the substance called current. They showed university students a series of circuit sketches that included different numbers of lamps in each circuit, including the case of no lamps (i.e., a battery with a wire connecting its terminals together). When asked about the relative amounts of current in the various circuits, 50% of the participants responded that the same fixed amount of current would flow from the battery in all

[15]Resistors are special devices whose sole purpose is to introduce resistance into the circuit. They are used widely in circuits to reduce the current flow for particular applications. Resistors typically emit heat when the current flows through them.

cases—even when no lamps were present in the circuit.[16] Said one student, “I just don’t see how I’d see that much difference whether the lightbulb is there or not—isn’t the current the same all the time?” (p. 997). Maichle (1982) reported similar beliefs within populations of both high school and university students. It, thus, appears that one property of the naive conception of current is that it can be stored away in batteries.

Novices also have a strong belief in the consumability of current. This belief has been identified and tested perhaps more widely than any other naive conception in electricity. Many researchers (e.g., Fredette & Lockhead, 1980; Gott, 1985; McDermott & van Zee, 1984; Shipstone, 1984; Tiberghien, 1979) outlined in their reports this basic belief that current is used up by devices like a sort of fuel. More current enters into a lamp than departs it because the lamp is said to “consume” some of the current to shine. Some students believe that no current departs the lamp whatsoever (Cosgrove & Osborne, 1985). A reliable test of this belief was briefly described earlier in this section. Students are shown pictures of circuits that contain a varying number of lightbulbs. They are then asked about the relative brightness of the lamps within a single circuit. The scientifically correct response, of course, is that all lamps will shine with equal brightness. However, if current is indeed consumed, then the first lamp in the circuit should shine most brightly, with subsequent lamps receiving attenuated amounts of current and thus shining more dimly. McDermott and van Zee observed that more than one third of university students think that, in a two-bulb circuit, the second bulb will be dimmer than the first. Gott extended this finding by showing high school students a circuit containing five lamps. In this case, a large majority (73%) of participants predicted that there would be differences in the brightness of the various bulbs.

Voltage is a substance. If novices are able to explain the workings of electrical circuits by appealing only to their ideas about current, wires, lamps, and batteries (as simple storage for current), then they encounter problems when asked to make sense of voltage. Many novices believe that voltage is just another term for current. McDermott and van Zee (1984) observed that, in discussing their predictions about circuits, university students frequently interchanged the words *current, energy, power, voltage,* and even *electricity*. Novices might fail to distinguish among these various concepts, perhaps, because they already have a satisfying explanatory model of how a circuit works. Maichle (1982) identified the naive belief that voltage exists only in the presence of current. Approximately 70% of his participants disagreed with the suggestion that voltage can exist even when there is no current when, in fact, the statement is true. An even greater majority of participants

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[16]Of course this response is not true. Two lamps in the circuit will present twice the resistance to the battery, so that by Ohm’s Law, we would expect half of the current. The two lamps should glow only half as brightly as a single lamp.

agreed with the suggestion that voltage is actually part of current. Maichle continued to probe for a more exact description of how novices think of voltage but encountered a number of diverging opinions. Although approximately 30% of his participants thought that voltage is the intensity or force of current, another 15% agreed that voltage and current are identical. Thus, voltage and current are expected by most novices to appear together in electrical circuits, although the relation between the two is unclear.

Voltage is the amount of substance in the battery. One interpretation of voltage, which is consistent with naive conceptions of electrical current, is that it is a measure of the amount of current in the battery. A fully charged battery's voltage is, thus, related to its storage capacity for current. As mentioned before, this belief has been identified by McDermott and van Zee (1984) as well as Rhoneck (1986). More direct evidence has been provided by Reiner and Shauble (1988), who observed that students associate larger batteries with larger amounts of stored current. Students drew the additional conclusion that a higher voltage implied a longer lasting battery, presumably because of the greater amount of stored current. Still another interpretation of voltage mentioned before (Maichle, 1982) is that novices think of voltage as a property that defines the nature of the current. Specifically, voltage is thought of as the force, strength, or density of the electrical current. For example, Rhoneck interviewed novices concerning the current obtained from a drained battery. Their summarized response was that the current is "weaker" because it has fewer particles in it. Rhoneck concluded from this observation that novices associate voltage with the current density, which serves as their conception of the current's force.

From the discussion in the previous sections, we recognize that naive conceptualization of voltage and current are not consistent between ages or types of problems. Nonetheless, this review has consistently drawn support for the idea that students often rely on materialistic conceptions of electricity. Although some novices conceptualize voltage as an actual substance, perhaps failing to differentiate between voltage and current, others attribute voltage with properties of current, such as its density or force.

IMPLICATIONS FOR TEACHING

Use of Materialistic Models by Physics Experts

Many subdisciplines within physics make use of materialistic models, particularly in informal contexts. Clement (1988), among others, suggested that physics intuition (which is presumably drawn on by physics experts and novices alike) is "concrete" or materialistic in nature. Hence, we might expect that such materialistic models are used by physicists to maintain an intuitive grasp of a topic and are then abandoned for more abstract representations when the need arises. Light, for example, is often described as a stream of particles rather than as the propagation of an electromagnetic wave. Such materialistic models can be modified, when necessary, to accommodate finer theoretical points. In this example, most physicists would be quick to mention that the light particles (*photons*) have no size or mass when at rest, that each particle possesses a certain characteristic energy, and so forth, until the model was "corrected" to the desired level of accuracy. Finally, due to the immaterial nature of light itself, the materialistic model will be invalid. Expert physicists presumably know when such "incomplete" models will be useful and when they will do more harm than good. It is interesting that they should ever prefer a limited, or even flawed, model, but apparently there is some advantage to having concrete, materialistic conceptions.

Slotta, Chi, and Joram (1995) interviewed expert physicists (graduate students and postdoctoral students) concerning their explanations of qualitative problems in light, heat, and electricity and found that the use of such incomplete, informal materialistic models is quite common. For example, experimental physicists sometimes described electrical resistance as a stream of electrons slowly trying to "flow" through a vibrating lattice of metal atoms. As in the previous example, this model is far removed from the accepted theoretical view but can be "doctored up" until it is a much better approximation (e.g., by giving all of the electrons some very large, but randomly directed, velocity; by introducing the idea of "holes" in electron "shells"; etc.). Incomplete, materialistic models are also used in the domain of particle physics, especially with regard to Feynman diagrams, which serve to represent mathematical integrations of abstract field variables but can be readily interpreted as analog diagrams of actual particle trajectories through space and time.

It is apparent that physicists make regular use of materialistic models, at least in their informal reasoning. Perhaps this is because it is fundamentally more simple to form conceptualizations that are concrete or easily imaginable. Slotta et al. (1995) found no examples of physicists falling prey to these materialistic notions (e.g., by arriving at incorrect solutions).[17] Thus, it appears that limited, materialistic models of abstract physics concepts are not necessarily a damaging source of misconceptions—at least not to those who are aware of and work within their limitations. It would be premature to say that materialistic conceptions are directly responsible for the persistence of naive misconceptions. Rather, it may be a matter of knowing when the materialistic view is appropriate and when that view should be abandoned for a more sophisticated, nonmaterial conceptualization (see Chi, 1992, 1997; Chi & Slotta, 1993).

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[17]There are, however, examples of expert physicists falling prey to the same misconceptions exhibited by novices (McDermott, 1984). This seems to indicate that the substance schema, although not relied on in expert reasoning, remains intact as a knowledge structure.

Use of Materialistic Models in Physics Instruction

Research on student misconceptions has been driven largely by an interest in the development of a cognitive theory of instruction (Glaser, 1976; Resnick, 1983). An understanding of the nature of student misconceptions should provide clues about the structure of knowledge as well as the cognitive processes by which such knowledge becomes revised. Clearly, such understanding will lead to insights about the processes involved in instruction. This review has identified one aspect of student misconceptions that is common only to notoriously difficult physics concepts,[18] such as light, heat, electricity, and force. As our review suggests, physics novices persistently misconceive these concepts as if they are material substances or have properties of material substances. Furthermore, instructional efforts to directly confront these misconceptions (e.g., by presenting contradictory evidence) are typically unsuccessful,[19] perhaps because the actual physics theory is so conceptually dissimilar to any substance-based view. Chinn and Brewer (1993) discussed a variety of different ways in which students manage to assimilate instructional messages that run counter to their existing conceptions (e.g., the contradictory evidence is ignored or rejected, excluded from analysis, or held in abeyance). Thus, there is an interesting question concerning the most effective way of instructing these concepts.

We wish to avoid the overly zealous interpretation of this review that materialism in any capacity should be avoided by instruction or wiped out wherever it is encountered. Indeed, the question remains as to what extent materialistic models should be used in the instruction of abstract physics topics such as force, light, heat, and electricity. Clement (1987) suggested that naive materialistic conceptions might provide a good starting point for instruction and that a theoretically consistent model can be approached by means of bridging analogies. Similarly, it might be that students would perish without some use of familiar materialistic terms, which provide a comfortable base from which to interpret new information, as suggested by Johnson (1987) and Lakoff (1987). Johnson argued that we (as learners) develop "image schemata, which are abstract patterns in our experience and understanding that are not prepositional in any of the standard sense of that term, and yet they are central to meaning and to inferences we make" (p. 2). To simply start presenting basic physics concepts through nonmaterialistic representations (e.g., electric fields) might strip the students of all of the tools and experience patterns they have constructed to make sense of things. Thus, to completely ignore a student's existing materialistic conceptions and avoid materialistic language altogether may not be the most effective means of instruction.

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[18]Note that these concepts have received so much attention in the research literature precisely because they are concepts that have traditionally been problematic for students.

[19]Chi (1992; Chi, Slotta, & deLeeuw, 1994) provided further discussion of the robust characteristics of these misconceptions.

Another important question is whether and to what extent instruction should attempt to directly confront students' materialistic conceptions of light, heat, electricity, or force (Slotta & Chi, 2000; Slotta et al., 1995). It is possible that some physics concepts should be addressed through materialistic models, whereas the instruction of others should strictly avoid materialistic analogies. Chi (1992; Chi & Slotta, 1993; Slotta et al., 1995) proposed a theory of conceptual change in which she accounts for the materialistic commitments of physics novices. She proposed that these four concepts (among others) are attributed by novices with ontological properties, based on their existing corpus of conceptual knowledge about substances. Perhaps because of linguistic cues (e.g., "shut the door, you're letting all the heat out") or perceptual ones (e.g., "streams" of light), these concepts are categorized by novices as *material substances*. As far as physicists are concerned, they should actually be thought of as belonging to a special category known as *equilibration processes.* Naive conceptions of these topics are so robust because of a resistance or inability to change these ontological categorizations. A possible implication for physics instruction is that materialistic models should be avoided altogether in teaching such concepts. In these cases, instruction should attempt to introduce a new language of processes while shunning any language that uses the ontological attributes of material substances. This could be achieved by making use of visual simulations and tailored instruction about the *process* category to help expose students to novel ontological attributes (e.g., simultaneity, independence, or equilibrium-seeking). Slotta and Chi (2000) applied such an instructional intervention for the concept of electric current and demonstrated its effectiveness.

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