THE JOURNAL OF THE LEARNING SCIENCES, *14*(2), 161–199

Commonsense Conceptions of Emergent Processes: Why Some Misconceptions Are Robust

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This article offers a plausible domain-general explanation for why some concepts of processes are resistant to instructional remediation although other, apparently similar concepts are more easily understood. The explanation assumes that processes may differ in ontological ways: that some processes (such as the apparent flow in diffusion of dye in water) are *emergent* and other processes (such as the flow of blood in human circulation) are *direct*. Although precise definition of the two kinds of processes are probably impossible, attributes of direct and emergent processes are described that distinguish them in a domain-general way.

Circulation and diffusion, which are used as examples of direct and emergent processes, are associated with different kinds of misconceptions. The claim is that students' misconceptions for direct kinds of processes, such as blood circulation, are of the same ontological kind as the correct conception, suggesting that misconceptions of direct processes may be nonrobust. However, students' misconceptions of emergent processes are robust because they misinterpret emergent processes as a kind of commonsense direct processes. To correct such a misconception requires a re-representation or a conceptual shift across ontological kinds. Therefore, misconceptions of emergent processes are robust because such a shift requires that students know about the emergent kind and can overcome their (perhaps even innate) predisposition to conceive of all processes as a direct kind.

Such a domain-general explanation suggests that teaching students the causal structure underlying emergent processes may enable them to recognize and understand a variety of emergent processes for which they have robust misconceptions, such as concepts of electricity, heat and temperature, and evolution.

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Many science concepts are extremely hard for middle and high school students to learn with deep understanding. This lack of deep understanding is displayed in their naïve explanations for various concepts and phenomena, such as giraffes having long necks, electricity, and sound transmission. As of 1993, over 3,000 studies had documented the existence of naïve conceptions in science (see Pfundt & Duit, 1993), in the hope of understanding how they can inform instruction. Several recent reviews survey these studies and further highlight their prevalence (see Confrey, 1990; Driver, Squires, Rushworth & Wood-Robinson, 1994; Ram, Nersessian, & Keil, 1997; Reiner, Slotta, Chi & Resnick, 2000). Students' naïve explanations, which are often called misconceptions, are claimed to be stable, robust, and resistant to instruction (Anderson & Smith, 1987). Even innovative instructional interventions (e.g., through confrontational methods in which the students' answers are shown to be in direct conflict with the observed physical outcome), have generally failed to improve their understanding (Champagne, Gunstone Klopfer, 1985; Dreyfus, Jungwirth & Eliovitch, 1990; Hake, 1998).

Misconceptions have been portrayed in one of two ways: as either fragmented or coherent. A fragmented view considers misconceptions as "a set of loosely connected and reinforcing ideas" (diSessa, 1988). diSessa (1988) viewed intuitive physics as consisting of "a rather large number of fragments" (p. 52) that he calls "p-prims" or phenomenological primitives, which are simple abstractions for common everyday experiences. For example, a misconception such as that *a force is a push or a pull* (Minstrell and Stimpson; 1986), is a simple abstraction of a common everyday observation of a throw. Therefore, the misconception (that *a force is a push or a pull*) is generated by a simple p-prim called "force as a mover". Similarly, the misconception that *continuing motion implies a continued force in the direction of the movement* (Clement, 1982) is generated from a p-prim called "continuous force ," which can be abstracted from common everyday experiences of needing constant effort to keep an object in motion. In this fragmented view, students' naïve explanations for a process such as the motion of a toss of a ball, can be generated by combining several p-prims

In contrast, a coherent view claims that misconceptions are *not merely* inaccurate or incomplete isolated pieces of knowledge (with respect to the correct scientific conceptions), but rather, they can be portrayed as *alternative* conceptions. As Anderson and Smith (1987) put it, "there are consistent understandable patterns in the incorrect answers that students give." (p. 90). This "pattern" of coherence is captured in different ways by different investigators. Early on, researchers imposed coherence by noting a resemblance between students' naïve explanations and the explanations of medieval scientists. Therefore, students' naïve explanations were considered to be "theory-like" because there is a correspondence in their assumptions with those held by medieval scientists. For example, students' naïve notions about motion are similar to the impetus theory discussed by Buridan in the 14th century in that both the naïve notions and the impetus theory assume (a) that an object set in motion acquires an internal force and this internal force (impetus) keeps the object in motion and (b) that a moving object's impetus gradually dissipates so that the object gradually slows down and comes to a stop (McCloskey, 1983). The same logic was used by Wiser (1987) to claim a theory-like view by showing a correspondence between students' naïve conceptions of heat and temperature and medieval scientists' source-recipient model.

More recently, patterns of coherence in students' naïve explanations have been captured by identifying the kind of mental models students held from which misconceptions were generated. For example, Vosniadou and Brewer (1992) identified various kinds of naïve mental models of the earth that young children held. Similarly, Chi, de Leeuw, Chiu and LaVancher (1994) captured the various kinds of flawed mental models of the human circulatory system that middle school children held. Seeing a systematicity and patterns in students' naïve explanations often require a methodology that involves a more thorough and extensive exploration, such as having students answer numerous generative questions (Vosniadou & Brewer, 1992) or coding the verbal explanations in several ways to get a converging interpretation of their misunderstanding (Chi, de Leeuw, et al., 1994).[1]

Regardless of whether naïve explanations are assumed to be fragmented or coherent, both views characterized naïve explanations from a *domain-specific* perspective, in either a *concept-specific* or a *theory-specific* way. For example, a *concept-specific* view of naïve explanations of force is to claim that they resemble everyday conceptions of "force"; and a *theory-specific* view of naïve explanations of heat and temperature is to claim that they resemble medieval "source-recipient theories" of heat and temperature. The goal of this article, however, is to characterize the underlying nature of naïve explanations from a *domain-general* perspective, at neither a concept nor a theory level but rather at an "ontological" level. A *domain-general* perspective is potentially powerful in two ways: It can explain why a variety of misconceptions are so robust and persistent and it can prescribe instructional intervention that might generalize across domains and concepts.

The gist of the domain-general approach for characterizing misconceptions can be summarized by the following postulates. First, this perspective assumes that there are underlying commonalities that exist across a diverse set of formal (i.e., those taught in a science curriculum) and everyday phenomena (i.e., those encountered in daily life which may or may not be discussed in school). Second, these commonalities can be construed as attributes of an ontological kind or category. Ontological categories refer to the basic categories of realities or the kinds of exis-

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[1] In both of these cases, we are not claiming that flawed mental models of the earth and flawed mental models of the circulatory system are robust misconceptions, as will become evident later in this article. These two examples are cited here to illustrate a methodology of capturing patterns of coherence. However, this type of methodology can be used to capture coherence of concepts that are robustly misconceived, such as speciation (Samarapungavan & Wiers, 1997).

tent in the world, such as concrete objects, events, and abstractions. For example, entities and events are distinct ontological categories in that they are differentiated by mutually exclusive sets of *plausible* attributes. An ontological attribute is one that a category member may plausibly have, but not characteristically nor necessarily has (Chi, 1997a; Chi & Roscoe, 2002).[2] An entity, such as a bit of glass, can be colored even though it is colorless (Sommers, 1971), whereas an event, such as a baseball game, cannot be colored. Therefore, being able to be colored is an ontological attribute of entities but not of events. People's conception of ontological categories is referred to as their ontological *knowledge* (Keil, 1979). Third, a student's ontological knowledge and the actual ontological categories may or may not correspond. That is, one's *conception* may not match *reality*, at the ontological level. Fourth, assuming that assigning phenomena into ontological categories is a fundamental human capability (Lakoff, 1987), then many robust misconceptions can be interpreted as a mismatch between conception and reality at the ontological level, rather than (and in addition to) at the concept-specific and theory-specific level. In this view, robust misconceptions are mis-categorizations *across* ontological boundaries in that a member of one ontological category is misrepresented as a member of another ontological category. Finally, alternative conceptions *within* an ontological category should be less entrenched and robust, meaning that they should be more readily resolved through learning, than misconceptions *across* ontological categories.

The current thesis has evolved over the last decade. Our prior analyses were incomplete in several ways and have metamorphosed several times. The metamorphosis is reflected in the various names we have used (many incorrectly) over the years to refer to emergent processes, ranging from "events" (Chi, 1992), to "acausal interaction processes" (Chi, 1993; Chi & Slotta, 1993), to "constraint-based interactions" (Chi, de Leeuw, et al., 1994; Slotta, Chi & Joram, 1995; Slotta & Chi, 1996), to "equilibration processes" (Chi, 1997a; Ferrari & Chi, 1998), to "complicated, abstract and dynamic concepts" (Chi, 2000a), and to "complex, dynamic processes" (Chi & Roscoe, 2002). The evolution of names reflects our improved understanding. More recently, we have used these ideas to discriminate between robust and non-robust misconceptions (Chi & Roscoe, 2002), as well as to apply some of these ideas to scientific discoveries (Chi & Hausmann, 2003).

This article represents a more complete but still evolving exposition of this theoretical explanation. It has five sections. In the first section, two ontologically dis-

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[2] Ontological attributes differ from characteristic or defining features (those typically explored by psychologists, see Smith, 1989), in that characteristic and defining features are those that a category member typically has or must have, respectively. Therefore, people identify a natural object or concept by categorizing it, often on the basis of characteristic features that it most likely has (such as the red color for a cardinal), whereas people identify a nominal concept such as kinship (e.g., an aunt), law (e.g. felony), or geometry (e.g., a triangle), on the basis of defining features that it must have.

tinct kinds of scientific processes, “direct” and “emergent ,” are described on the basis of how texts explain them, followed by brief analyses of the text explanations. The second section shows the differential rate of successes with which these two kinds of processes are learned. In the third section, these two kinds of processes are then distinguished ontologically by their mechanisms of causality, as the source of their differential learning outcomes. This distinction was derived from analyses of both the concepts and students’ misconceptions of them. The fourth section illustrates how students do tend to misconceive the “emergent” kind of processes as the “direct” kind, supporting the conjecture proposed here. Finally, the last section discusses several caveats as well as compares this explanation to alternative explanations, and their implications for instructional approaches.

Because misconceptions are similarly generated even for concepts introduced in the middle school curricula, this article will focus on these more elementary concepts as examples not only because these concepts are foundational and important to learn with deep understanding, but also for expositional purpose, they are more simplistic and easier to describe in non-technical terms. Therefore, this article will address primarily concepts that are introduced in the middle school curricula.

TEXT EXPLANATIONS AND ANALYSES OF TWO FLOW PROCESSES

In this section, two flow processes will be described: the flow of blood in the human circulatory system and the apparent flow of dye dropped into a container of water in diffusion. The choice of these two processes is guided by numerous considerations. First, they are both processes that are typically covered in middle school (in 8th grade) and sometimes again in high school. Second, they are both important and foundational concepts. Circulation has been ranked in the top five most important topics to be learned in biology (Stewart, 1982; but the other four topics are not introduced in the lower grades) and diffusion is a “fundamental concept associated with natural phenomena throughout the natural sciences” (Marek, Cowan, & Cavallo, 1994), such as the exchange of oxygen and carbon dioxide in the cells. Third, misconceptions have been identified in the literature for both concepts. Discussion of these two concepts using laymen’s terminologies now follows.

Circulation: An Analysis of Text Explanations

In a popular middle school text such as *Modern Biology* (Towle, 1989), blood circulation is explained by a passage of around 100 sentences. Such a passage introduces the circulatory system by defining its global function (of distributing oxygen, hormones and nutrients to all cells in the body and removing carbon dioxide and wastes) and its three main components: the heart, vessels, and blood. It describes the paths of blood flows along with discussing the components in detail, sometimes reducing a component to its subcomponents, such as describing the septum and the pericardium of the heart. Typically, the structure and behavior of the components are discussed, whereas the function of a component and the structure-function relations are sometimes omitted.

There are at least three key ideas about the path of blood flow in circulation that are not explicitly emphasized in such a passage. One key idea is that the lungs, an important component of circulation, are not merely a body part to which blood has to traverse en route to or from another body part. A second key idea is that the lungs (and not the heart) are the site of oxygen and carbon dioxide exchange. A third key idea is that there are a double (pulmonary and systemic) paths (rather than a single path) of blood flow. That is, blood from the right ventricle is pumped to the lungs to be oxygenated, whereas blood from the left ventricle is pumped to the rest of the body to deliver oxygen. Therefore, one path transports de-oxygenated blood to receive oxygen while the other path transports oxygenated blood to deliver oxygen (Chi, 2000b). Failing to infer these three key ideas will contribute toward misconceptions, as will be seen later.

Diffusion: An Analysis of Text Explanations

The classic middle school textbook presents this flow phenomenon in the context of the following example (Marek, et al., 1994):

> A 10-gallon glass container is full of clear water. Several drops of a dark blue dye are dropped on the surface of the water. The dye begins to swirl, then spreads throughout the water. Eventually the water changes from colorless to light blue. (p. 75)

However, to explain this phenomenon more easily, let's take the diffusion of two colored liquids, initially contained in two separate beakers, as our example. Figure 1 (the top half) shows one beaker containing dark blue dye (mixed with water), and the other beaker containing regular clear water.[3] At some point, suppose the two beakers are connected with a large clear tube so that the liquid from the two containers comes in contact with each other. Over time, it appears as if the dark blue liquid flows into the beaker with the clear liquid, until both beakers reach the same color of medium blue. At that point, the blue liquid seems to stop flowing. (The wavy arrow in the upper portion of Figure 1 depicts this perceptible flow pattern.)

This flow pattern is sometimes referred to as the macro level pattern, in the sense that it is a visible aggregate level phenomenon, consisting of the aggregate

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[3] To exaggerate our point and to simplify the discussion throughout, the dyed water is shown (and referred to) as containing only dye molecules. In reality, dyed water contains both dye and water molecules.

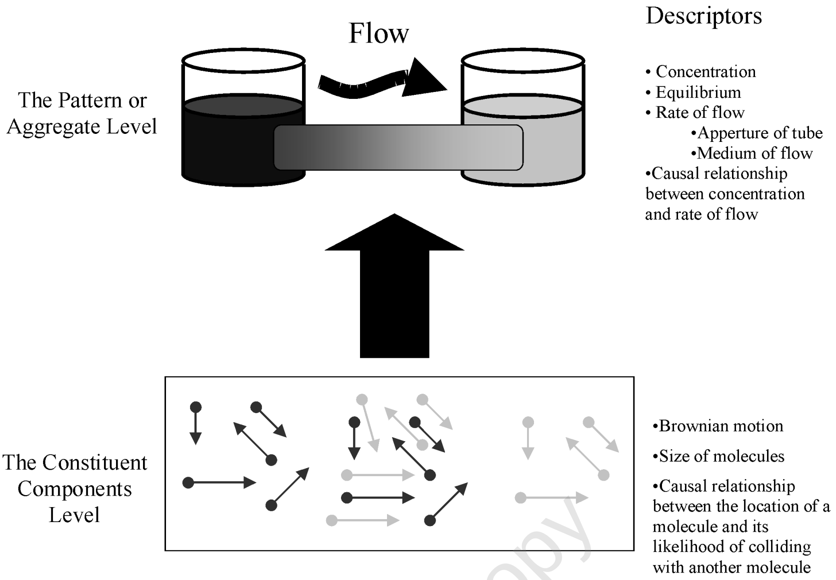

FIGURE 1 The pattern and the constituent components levels and their distinct descriptors of an emergent process, diffusion.

components dark blue and clear liquids. *What causes the flow pattern to arise*? A typical text explanation to this question refers to the difference in the "concentration" of the dye in the two solutions, such as:

> Diffusion is the process by which molecules of a substance move from areas of higher concentration of that substance to areas of lower concentration of that substance. (Maton et al., 1995, p. 83)

Although "concentration" is not an easy concept for students, it can be understood simply as "the quantity of solute (i.e. dye) dissolved in a given quantity of solution (i.e. water)" (Dobson, Holman, & Roberts, 2001, p. 196). Various texts can also describe many other *factors* (such as conditions and variables) affecting this flow pattern, such as when it stops (at "equilibrium"), how it can be sped up (raising the temperature of the water solution, i.e., or changing the medium of the solution from water to another substance).

However, the typical explanation posed above is *descriptive* in that it specifies the conditions (e.g., the concentration difference) and variables affecting the macro level flow. It does not explain the *causal mechanism* of how or why this flow pattern arises. The same text's explanation to the question of *why does diffusion occur,* is:

> Molecules of all substances are in constant motion, colliding continuously with one another. This motion causes the molecules to spread out. The molecules move from an area where there are more of them (higher concentration) to an area where there are fewer of them (lower concentration). (Maton et al., 1995, p. 84)

Such an explanation of the mechanism contains three important aspects. First, it accurately describes the motion of the molecules, both the molecules' action (that they move continuously) and their interactions (that they collide continuously). Second, the explanation correctly attributes the cause of the flow to this motion (in that it causes the molecules to spread out). Third, the explanation reduces the aggregate components (the two colored liquids) into its constituents, in this case, the dye molecules for the dark blue dye liquid and the water molecules for the clear liquid. Therefore, each aggregate component is made up of molecules of one kind. The molecular level is often referred to as the micro level.

However, as in the case of circulation, such an explanation blurs several key ideas that can cause misconceptions. First, merely stating that "the molecules are in constant motion, colliding continuously with one another" does not emphasize the randomness of the molecules' *interactions* (i.e., any molecule, whether dye or water, can interact unpredictably with any other molecule). Even if a text goes into the details of Brownian motion, that will only specify the randomness of molecules' independent *actions,* in the sense that randomness refers to the unpredictable locations to which a molecule will move as it jitters around. The randomness of a molecule's action is distinct from the randomness of molecules' interactions. Second, saying that the molecules move from an area of higher concentration to an area of lower concentration suggests that only the dye molecules move (corresponding to the apparent flow of the dye liquid), rather than that all molecules move around. Third, saying that molecules move from an area of high to low concentration also suggests that the movement of the molecules are directional, whereas in fact molecules move in all directions, and some molecules can move from low to high. Fourth, by omitting a few other key points, such an explanation can also mislead students into thinking that the dye molecules spread out only until the state of "equilibrium ," then they stop spreading; when in fact the molecules will continue to act and interact even after equilibrium is reached. Finally, it fails to emphasize that all the molecules must be treated as a "population ," in that the motion of all the molecules must be considered collectively to explain the flow pattern. Consider all the molecules as a collection also implies that all their movements are the same; and not that some (the dye) molecules move from high to low concentration while others (the water) stay in place. Therefore, even though the text explanation has decomposed the aggregate components of liquids to its constituent components of molecules, the explanation of the mechanism is still misleading, so that students can come away with misconceptions even though the text explained the mechanism at the molecular level.

So what causes the flow pattern to arise, from the perspective of the mechanism? The flow pattern arises from the following simple mechanism. Because, at the initial boundary between the dye and water (that is, the boundary where dye and water come into contact inside the tube), the dye molecules are likely to collide into or past the water molecules, thereby occupying some of the space where only water molecules once occupied. (See the lower portion of Figure 1.) Likewise, the water molecules also bounce into and past the dye molecules and occupy some of the space that only dye molecules once occupied. Over time, the dye (or water) molecules are likely to occupy either the space where the water (or dye) molecules did occupy, merely from the dye and water molecules randomly bouncing into and past each other. This means that at times, some dye molecules can bounce backward into the blue liquid area as well. However, over time, at the macro level, it will seem as if the dye liquid is "moving into" the clear beaker. This is because the concentration of the dye molecules was originally restricted to the left beaker, and from random bouncing around and colliding, more and more dye molecules are likely to move to the right beaker. So, the flow pattern arises from a consideration of the *collective* (or net) effect of the constituent level interactions (i.e., the bouncing around and into each other) of *both* or *all* of the dye and water molecules, for each successive instance of time. (See the Appendix for an even more detailed explanation.)

This underlying mechanism relating the constituent component level behavior to the pattern level behavior can be described as one of *emergence,* in the sense that the pattern is the summative (or net) outcome of the random interactions of *all* the molecules (both dye and water), and not just due to the behavior of one class of molecules (such as the dye ones). Therefore, the causal mechanism between the constituent components and the pattern is a nondirect or *emergent* one (as shown by the solid arrow in Figure 1).

In sum, the analyses of text explanations show that in both cases, the text explanations are incomplete and misleading in that they did not emphasize information that addresses misconceptions, and they can in fact cause misconceptions.

THE DIFFERENTIAL LEARNING OUTCOMES OF THESE TWO PROCESSES

The claim that circulation and diffusion are two different kinds of processes suggests that one process ought to be more easily learned and understood than the other process. Is there such evidence? Fortunately there are data on the same age groups learning from the same text that can be compared. In the Chi, de Leeuw, et al. (1994) laboratory study, 24 8th-grade students were asked to read the passage of 101 sentences (a few less relevant sentences were deleted) from Towle's *Modern Biology* (1989) on the human circulatory system. Fourteen of the students were asked to self-explain in the course of reading and the other 10 were simply asked to read the passage twice. With such a simple instructional manipulation, the average gain from the pre-test to the post-test for the two groups was 32.6%, for a variety of easy-to-hard questions that tap information that was either presented explicitly or implicitly in the text (see Figure 2 in Chi, de Leeuw, et al., 1994). Therefore, with no direct instruction and spending only around 2 hr of self-instruction (either re-reading or self-explaining), students were able to answer correctly around 48% of the very hard and 78% of the easy questions.

A deeper way to measure students' learning and understanding is in terms of the changes in their mental models of the circulatory system. In that same study, during the pre-test, students were asked to define components of the circulatory system. Based on their responses, a 3-step procedure was developed that characterized their conception of blood flow in circulation in terms of five possible mental models, all flawed to varying degrees. (The procedure and flawed models are described in Chi, de Leeuw, el al., 1994, see Table 5.) For example, consider the following definition a student gave for the term "artery" (Chi, de Leeuw, et al., 1994):

> Artery is a general term for all tubes that are from the heart and they carry the clean blood from the heart to all the body… it [the body] always needs clean blood and the blood travels once through the arteries and when its used, it travels back up in the veins to go back to the heart, the heart cleans it again, umm, replenishes it with oxygen, umm and then it goes again to all the parts of the body. (p. 465)

This conception of circulation can be characterized as a "single loop" model: The student basically had only the notion of systemic circulation in which blood goes from the heart to all parts of the body, and then returns to the heart. Fifty percent (12/24) of the 8th grade students held this "single loop" model at the pre-test. Although half of the students started out with this flawed "single loop" model, after reading the circulation passage from *Modern Biology*, with or without generating self-explanations in the process of learning, only 1 student (or 4%) continued to maintain a "single loop" model. Moreover, 71% of the students had acquired the correct "double loop" model (see Table 5 in Chi, De Leeuw, et al., 1994).

In contrast, in a classroom study on diffusion with 100 10th grade students (Simpson & Marek, 1988), students' misunderstanding about diffusion remained after instruction using an earlier version of the same textbook *Modern Biology* (Otto, Towle & Madnick, 1983). Only about 3 students had "sound understanding" of diffusion. In a another similar study (Marek, 1986a), only 1 out of the 252 8th grade students showed "sound understanding" of diffusion. Clearly, from the same text, students seemed more capable of learning about the human circulatory system whereas they had great difficulties learning about the process of diffusion.

In sum, although in both cases students had misconceptions prior to instruction, and in both cases text explanations are often inadequate, nevertheless, it is clear that in the circulation case, their misconceptions were more correctable (or removed), whereas in the diffusion case, their misconceptions persisted and were more robust. Although many studies in the literature point out the existence of students' misconceptions, few (if any) studies point out the differential success with which these misconceptions can be removed (in the sense of learning the correct conceptions). Therefore, even though misconceptions for both circulation and diffusion were coherent and alternative, it is clear that they need to be discriminated on the basis of their ease of removal. In short, it may be more profitable for the debate in the literature to focus on explaining why some misconceptions may be more entrenched than others, and less on whether misconceptions are fragmented or coherent. The thesis of this article is an attempt to elucidate on this learning difference even though both kinds of misconceptions were coherent, and text explanations for both concepts were inadequate.

THE CAUSAL MECHANISMS OF THESE TWO KINDS OF FLOW PROCESSES

In this section, the nature of these two kinds of flow processes will be compared and contrasted, to understand why one kind of processes (such as circulation) might be more easily learned (i.e., the misconception seems to be corrected) than another kind of process (such as diffusion). There are many similarities between these two processes, besides the fact that they are both processes of flow. We start by pointing out their similarities, focusing especially on those that other researchers may have postulated as sources of misconceptions.

Their Similarities

First, both processes have global *patterns* and *components.* The global *patterns* of flow in both circulation and diffusion can be described in various ways, but the discussion here will focus on describing either its direction and speed. For example, in circulation, one of the blood path's direction of flow is from the heart to the lungs; and in diffusion, the direction of flow of the dye is from an area of greater concentration to an area of lesser concentration.

Second, for both kinds of processes, the components can be discussed at multiple *levels*. At the aggregate level, some of the components for circulation are the heart and veins, and the aggregate components for diffusion are the blue dye and clear liquids. For both processes, the aggregate components can be decomposed into their constituent level, such as red blood *cells* (& plasma) for blood or a different *set of cells* (or *tissue*) for the heart chambers and valves; and *molecules* for the dye and water liquids. Therefore, having multiple levels per se does not differentiate these two processes and thus cannot be a source of differential difficulty in learning one process over another process.

Third, the components of both processes *interact.* In the circulatory system, the heart interacts with blood by pumping it; the veins interact with blood by contracting and pushing it along. At a more constituent level, the valves (consisting of valve cells) open or close to prevent blood cells from moving in a specific direction. In diffusion, the aggregate components interact (the dye liquid flows into the clear liquid) and the constituent components also interact, in that the dye and water molecules collide with each other or not. So, interactions between the components, at both the aggregate and constituent levels, are a common feature of both of these processes.

Fourth, sometimes the pattern, as well as the aggregate and constituent components of both these processes may be invisible. In the case of blood circulation, it is difficult to see both the circulation pattern itself as well as its aggregate components (hearts and veins) and the constituent components (the cell tissues of the hearts and veins); and for diffusion, both the pattern and the aggregate components are visible but it is nearly impossible to see the constituent components (the individual water and dye molecules). Therefore, being invisible is not necessarily a source of difficulty either for accounting for the differential success of learning circulation over diffusion, especially given that more levels of circulation are invisible than diffusion.

Fifth, both processes involve numerous simple and complicated *descriptors* about both the pattern and the components. *Descriptor* is merely a generic term used here to refer to concepts and mechanisms and principles. The descriptors for the pattern of blood circulation involve simple concepts such as color of blood and complicated concepts such as pressure and elasticity and the descriptors for the pattern of diffusion also include simple concepts such as the color of the liquids and complicated concepts such as concentration and equilibrium. The descriptors for the components of circulation include simple concepts such as the size of the heart and complicated mechanism of heart tissue contraction, and the descriptors for the components of diffusion also include simple concepts such as the size of the molecules and more complicated mechanism of Brownian motion. (Examples of descriptors at each level for diffusion are shown in Figure 1). Therefore, for both kinds of processes, there is a rich set of descriptors (both simple and complicated) about both the components and the pattern that needs to be learned to understand the processes completely. One would be hard pressed to claim though that the descriptors of one process (such as diffusion) is more difficult to understand than the descriptors of another process (such as circulation), thereby contributing to the difficulty of learning one process over another.

Finally, various factors (conditions or variables) can influence both the global patterns of flow and the local specific behavior of the components. For example, in diffusion, any of the following global variables (the concentration of dye molecules in the original beaker, the size of the aperture of the tube connecting the two containers in the scenario depicted in Figure 1, the temperature of the solution), can cause the rate of flow to increase or decrease; and in circulation, any of the following factors (the force of contraction of the heart and the veins, the thickening of the arteries, which is comparable to the size of the aperture in the diffusion above, and whether or not the person is taking blood thinner), can also affect the speed of blood flow. Similarly, many local factors can influence a component's behavior. For example, in diffusion, a factor such as the proximity of neighboring molecules can cause a specific outcome (such as whether a molecule collides with or bypasses another molecule), and in circulation, a local factor such as how properly the valve between the atrium and the ventricle closes can determine whether or not blood leaks back into the atrium. Therefore, the specific behavior of the individual components or their constituents, depend on some local conditions. Therefore, there are many *cause-effect relations* between some conditions or factors that either affects the global pattern or the local behaviors of the components.

Although students may be ignorant of many of these cause-effect relations between the factors and the pattern and/or the components, they may be straightforward to learn if taught. For example, students can learn that heat flows faster in a medium such as a silver bar than a wood bar, when presented with an animation of these two kind of bars (Linn & Hsi, 2000, p.92). However, understanding how certain factors influence the behavior for either the pattern or the components does not mean that students understand *why* the pattern is obtained in the first place, or *how* the behavior of the components causes the behavior of the pattern. Therefore, understanding the *causal mechanism between the components and the pattern,* is distinct from understanding the *cause-effect relations between some factors and the pattern and/or the components.* The former will be referred to as the *causal mechanism* (between the components and the pattern), and the latter as the *cause-effect relations* (between some factors and the pattern and/or the components). Again, the prediction here is that these cause-effect relations may not be the source of differential difficulty of learning one process over another process.

In sum, both processes share several similar features. These processes have a *pattern* and *components.* The components may have multiple *levels* and they *interact* at all levels. Sometimes both the pattern and the components may be *invisible*. The *descriptors* of both the components and the pattern can be infinitely complicated. And finally, there exist many factors that can influence or cause the behavior of both the pattern and the components to change. Understanding these *cause–effect relationships*, however, does not necessarily mean that students then understand the *mechanisms* of *how* or *why* some processes exhibit the patterns that they do, such as the flow in diffusion. The thesis of this article is to suggest that these similarities cannot in principle be the sources of differential learning of these two processes.

Their Differences

Although the two flow processes share many similarities, they are fundamentally distinct. Basically, these two processes differ in the *mechanism* that causes the flow—that is *how* the structure (or behavior or function) of the components causes the pattern to occur. In the one case, blood circulation, the nature of the aggregate components or their constituents (such the structure of the chambers of the heart and the strategic placement of the valves in the heart) are *directly* causing the global pattern of flow, such as its direction and speed. For example, because blood enters the upper chamber, the direction of flow is downward toward the lower chamber. Therefore, the direction of flow is determined directly by the way the chambers are structured as well as the way the vessels are connected. Similarly, the behavior of chambers in terms of how quickly it ejects blood, specifies directly the speed of blood flow. Therefore, this type of processes can be referred as as *direct* (acknowledging that the effect can also be indirect, in the sense that the outcome might be mediated by some intermediate process).

In contrast, for a process such as diffusion, neither the aggregate components themselves (the dye and clear liquids) nor their constituents (dye and water molecules) are directly (nor indirectly) causing the global flow pattern to occur. Instead, the mechanism of the flow must be explained in terms of the *collective* interactive outcomes of *all the* constituent components (both the dye and water molecules), such that neither an individual component (such as the dye liquid) nor a group of individual constituent components (such as all the dye molecules) cause(s) the global pattern (or the dye to flow). Therefore, the mechanism of flow in a diffusion kind of process is nondirect and can be referred to as *emergent.*

To see more clearly that direct and emergent processes are really different kinds, the sections below describe three ways in which they are fundamentally different. The first difference refers to the behaviors of the components. The second difference refers to the treatment of the components as either classes or collection. And the third difference refers to the causal mechanisms relating the components and the pattern.

Differences in the Behavior of the Components at the Constituent Level

Earlier, it was mentioned that the components of both circulation and diffusion can be discussed at multiple levels. For circulation, the aggregate components are the heart and veins; the heart can be decomposed further into its chambers and valves in the chamber, which in turn can be reduced further into its constituents, such as cells. Because the composition of many of these components are made up of one types of cells (or tissue), a component in circulation, for example, will be referred to as the atrium, and the constituents of the atrium will be referred to either as the atrium cells or the atrium tissue. Five attributes distinguish the behavior of the constituent components of direct and emergent processes. These are summarized in the upper section of Table 1 and described in detail later.

Distinct versus uniform kinds of behavior. What distinguishes direct from emergent processes is the relative uniformity of how their constituent components behave. For direct processes, the behaviors of the various constituent compo-

TABLE 1
Ontological Attributes of Direct and Emergent Processes

	Direct Processes	*Emergent Processes*
Component Level Interactions	1. Distinct	Uniform
	2. Constrained	Unconstrained (random)
	3. Sequential	Simultaneous
	4. Dependent	Independent
	5. Terminating	Continuous
Component–pattern relations	6. Subgroups (or classes)	All components (or a collection of components)
	7. Direct	Nondirect
	8. Corresponding	Disjoint
	9. Differential status	Equivalent status
	10. Global goal or intentional	Local goal or unintentional

nents are quite *distinct*. For example, in circulation, the behavior of the valve tissues (i.e., opening–closing to let blood flow or not) is distinct from the behavior of other constituent components, such as the chamber tissues in the heart (i.e., to contract or relax, so that blood is either ejected or accumulated). Therefore, the behaviors of the various constituent components are distinct. However, for emergent processes, the behavior of all the constituent components is *uniform*. Therefore, all the molecules behave in the same way, which is to collide with each other or not, regardless of whether they are dye or water molecules. Notice that the behavior of individual molecules need not be identical, even though they are of the same kind (i.e., uniform). For instance, they may bounce in different directions or different distances. But their behavior is basically of the same kind, which is to bounce around and collide into or past each other.

Unconstrained (or random) versus constrained interactions. Earlier, it was also mentioned that the components of both kinds of processes interact with each other. What distinguishes direct from emergent processes is the randomness with respect to with whom the components can interact. For direct processes, the interactions of the components are *constrained*, in the sense that each component can only interact with some pre-specified other components. For example, valves in veins interact with blood but they do not interact with the septum in the heart. Similarly, the atrium interacts with both blood and the ventricle but the atrium does not interact with the lungs. Note that because interactions of the components in circulation are constrained, one often describes their behaviors as if they are stand-alone actions such as *the heart pumps,* rather than interactions such as *the heart pumps blood.*

For emergent processes, however, the interactions of the constituent components are *unconstrained*. Both the dye and the water molecules can collide with any other dye and water molecules. Sometimes this is referred to as "random" interaction. But randomness in this unconstrained interaction sense should not be confused with the randomness of molecules' action in Brownian motion. The randomness in Brownian motion refers to the unpredictable location to which a molecule will move as it jitters around. Therefore, because randomness can refer to both the stand-alone *actions* as well as the *interactions* of molecules, to avoid misunderstanding, the term *unconstrained* will be used here to refer to the randomness of interactions.

Sequential versus simultaneous interactions. The two kinds of processes differ in terms of the temporal constraints on the interactions of the components. For direct processes, the components often interact in a *sequential* order. In circulation, the atrium tissue contracts and pushes blood through before the ventricle tissue contracts. For emergent processes on the other hand, all molecules in diffusion are colliding or passing each other *simultaneously* everywhere.

Dependent versus independent interactions. Related to the notion of sequential/simultaneous is the notion of dependent versus independent. The interactions of the components of a direct process are *dependent* upon each other whereas those of emergent processes are *independent*. For example, the ventricle tissue cannot contract until the atrium contracts, whereas whether one molecule collides with another molecule is independent of whether two other molecules elsewhere are colliding or not.

Terminating versus continuous interactions. The interactions of the components of a direct process *terminates* when the pattern of flow stops, whereas the constituent components of emergent processes *continue* their behaviors indefinitely. In circulation, if blood stops flowing, then the ventricle tissues must also have stopped contracting. In diffusion, however, even when the flow pattern stops (at equilibrium), the dye and water molecules continue to collide with or past each other.

Differences Between Classes and Collection

When the constituent components of emergent processes interact in the five ways characterized above, all of them can in essence be treated as members of a *collection*, whereas the constituent components of direct processes can be treated as members of different *classes* or *categories*. Below, I will propose why it might be easier to learn the structure of a class and to treat objects as members of a class rather than members of a collection. These are speculations because there is no literature that addresses learning issues in the context of classes and collection.

A *class* can be defined as denoting a category of objects whose members all *share* some characteristic or defining properties, such as appearance and structure. For example, all veins in circulation share similar structure, behavior and function, in that they are all tube-like vessels, they all contract, and their function is to push blood along. In circulation therefore, the components constitute a class of valves, a class of vessels, and each class has its own unique set of structure, behavior (or interactions with other classes) and function. When psychologists study concepts and categories, they are identifying class membership on the basis of shared properties (see Chi, 1997a, for a more elaborated discussion).

A collection, however, denotes a set of objects whose membership is not determined by their shared properties, but rather, by their interactions or interrelationships. For example, to determine whether a grove of trees is a forest (a collection), one must determine whether the trees are in the relationship of “close proximity” to each other. Therefore, membership in a collection is determined by the interrelationships among its members, and not by their shared features. Because the features of an object X are often a one-argument relation, such as the color of X, whereas the features of a collection are a two-argument relations, such as the relationship between X and Y, one could argue that classes are easier to learn and understand than collections.

Classes and collections also differ in terms of their part–whole relationships. That is, members of a class are also members of a super-class, whereas collections do not have this class-inclusion relationship. For example, a tree is a kind of plant, whereas a tree is not a kind of forest (Markman & Seibert, 1976). This means that members of a class can inherit properties of its super-class, whereas members of a collection cannot, thereby again making classes easier to learn.

The nature of classes might be easier to learn also because the shared features are often perceptually salient and can be intuitively grasped as similar (such as tube-like vessels) without the need of being told, whereas collections are less easily grasped because interrelationships are often not as perceptually salient as a visual feature. Therefore, we often need collections to be defined for us explicitly. For example, we understand the collection term *family* because we have been told that a person is a member of a family when he or she is *related by kinship* to the other members of that family, either as a parent, a sibling, and so forth.

Members of a collection, unfortunately, can also be construed as members of a class or sometimes multiple classes. For example, the trees in a forest might all be of one class (such as oak trees) or they may belong to several classes of trees, such as oak trees, pine trees, and so on, on the basis of their shared visual features. All pine trees, for example, are green and have a cone-like shape. Therefore, a grove of trees can be construed either as a forest or several classes of trees. Given that shared features (such as color and size) are more prominent than collection features, we are more likely to treat an unfamiliar group of objects (such as the dye and water molecules shown in the bottom of Figure 1) as two separate classes of molecules, rather than a collection of molecules. This perceptual salience of classes has also been forwarded as one explanation for young children’s failure at Piaget’s class inclusion task, which required that they attend to the collection rather than the classes (McGarrigle & Donaldson, 1974).

In essence, the five attributes of the components' behavior and interactions of an emergent process, mentioned above (and at the top of Table 1), could be construed as the *general* attributes that allow us to identify a group of objects as a collection. Even though we have been told (or taught) what the specific features of a collection is (such as proximity for a forest and kinship for a family), we have not necessarily been explicitly taught what the *general* attributes of a collection are. Therefore, a group of objects are members of a collection if all the objects have *uniform, unconstrained, simultaneous, independent, and continuous* interactions. For example, knowing the general features of a collection will allow us to treat a group of trees as a forest because it is obvious that all the trees grow near each other (*uniform* interaction), any tree can grow next to any other tree (*unconstrained* interaction), at the same time (*simultaneous* interaction), *independently* of which other tree grows next to another tree, and they *continue* to grow near each other even after a forest is formed. Therefore, without being told, these general attributes can guide us in identifying a group of objects as a collection when their behavior embodies (some of) these five features.

In sum, classes and collections are fundamentally distinct. A group of objects seems more readily conceived of as classes of objects rather than a collection. However, to understand many science concepts, the entire group of objects must be conceived of as a collection and not segregated into separate classes. To understand diffusion, both the dye and water molecules must be treated as a collection but students have a tendency to treat them as two separate classes (dye and water molecules) because the dye molecules share similar visual features (e.g., they all look blue) and the water molecules share an alternative set of visual features (as depicted in the bottom of Figure 1). Therefore, the tendency of humans to categorize objects on the basis of their shared features may work against us in trying to understand many science concepts, because these concepts require that we perceive the constituent components as a collection. This tendency to categorize on the basis of perceptually shared features may be another reason that explains the robustness of some misconceptions.

Differences in the Relation Between the Components and the Pattern

As asserted earlier, for both direct and emergent kinds of processes, the behaviors of the components (or their constituents) explain the pattern. The five differences in the way the constituent components interact in direct and emergent processes, described above, render five additional differences in the component-pattern relationships (or the causal mechanisms). They are described below and listed in Table 1, as attributes 6 to 10.

Subgroups (or classes) versus all of the components (or a collection). For direct processes, different *subgroups* or *classes* of components may have distinct identifiable roles and function that can contribute to different aspects of the pattern directly, whereas the components of an emergent process cannot be divided into subgroups with distinct roles or function. Rather, for emergent processes, the pattern is caused by considering the interactions of *all* the components, as a *collection.* In circulation, for example, the lungs play a role in only one path of blood circulation, the path from the right side of the heart; whereas blood from the left side of the heart does not go directly to the lungs. For diffusion, however, the interactions of all the molecules are responsible for the entire pattern of flow. There are no subgroups of molecules that collide only in the left beaker or only in the right beaker.

Direct versus nondirect effect. Related to the above, the behavior of the components of direct processes often *directly* or *indirectly* affect the pattern level, whereas in emergent processes, there is a *non-direct* effect of the behavior of any of the components on the pattern. For circulation, if there is a malfunctioning in one of the components, such as a hole in the septum, than the efficiency of circulation in the delivering of oxygen is directly compromised. For diffusion, on the other hand, the collision of any specific set of molecules have no direct or indirect effect on the flow. In fact, one can remove some molecules and one still would obtain a flow pattern.

Corresponding versus disjoint. For direct processes, it seems that the behavior of some of the components *correspond* to (or correlate with) the overall pattern of the process. In circulation for example, the direction of blood flow corresponds to the direction that valve opens–closes. For emergent processes, however the interactions at the component level is *disjoint* (or independent) from the behavior of the pattern. For example, in diffusion, the collisions and resulting movement of molecules can be in the opposite direction of the direction of flow.

Differential status (or contribution) versus equivalent status. For direct processes, often the interactions of some subgroup of the components are more responsible for the pattern, than some other components. In circulation, blood flow is much more impaired if a ventricle does not contract properly than the case of a heart valve not closing properly. Therefore, the pumping of the heart is clearly a more important interaction (rendering the heart a higher status) than the proper closing and opening of a heart valve. For emergent processes, however, the contributions of the interactions of all the components have *equal status*; one is not more or less important than another. Therefore, no collision among one set of molecules is more important than the collision of another set of molecules, with respect to its contribution toward the flow.

Global purpose (function/goal/intentional) versus local purpose (function/goal/unintentional). For direct processes, the behaviors of the components are teleological (or intentional) in the sense that they serve the purpose, function, or goal of the pattern. In circulation, the interactions of the components themselves, such as, the opening and closing of the valves to prevent blood from flowing backwards, serve the global function of delivering oxygen and nutrients and removing carbon dioxide and wastes. For emergent processes, on the other hand, none of the components interact with the purpose of producing a global goal (the observable pattern). The molecules merely move around in Brownian motion and collide with each other or not, without any intention of producing a flow pattern.

Summary of Differences of the Two Kinds of Flow Processes

Three differences between the two kinds of processes were described. Two of these differences are captured by the 10 mutually exclusive sets of attributes summarized in Table 1. The first set of 5 attributes contrasts the behavior of the (constituent) components. This set of attributes determines the second difference—whether the components should be treated as a collection or separate classes. This first set of attributes also dictates the kind of causal relations (the second set of 5 features) that exist between the components and the pattern. These are ontological attributes, which means that no process of either kind must have some characteristically few or all 10 of them. Rather, a process of each kind can plausibly have any of the 10 ontological attributes.

The 10 attributes are listed in a discrete way for the eventual purpose of training (as well as to see whether they contrast two ontological categories). It might be important to highlight each attribute separately for the ease of training, even though they are highly related. For example, the attributes of differential status and intentional goal (Attributes 9 & 10 in Table 1), plus the notions of a subgroup of one person (Attribute 6) having a direct effect (Attribute 7), when combined, form the idea of centralized control for direct processes and decentralized control for emergent processes. Centralized control means that people conceive of the global pattern as caused directly by the behavior of one or a few components (Resnick, 1996), such as misconceiving of bird flocking in a V-formation as being created by a "leader" bird at the front of the flock, who intentionally leads the other birds in a specific direction, when in fact bird flocking is a decentralized emergent phenomenon.

Because these 10 attributes are related, they can be summarized and described more qualitatively in the following way. Basically, to understand emergent processes, one must treat all the components as a uniform collection in which the individual components should not be differentiated from each other. As a collection, therefore, the individual components can interact with any other component. The pattern that one observes in the process emerges from the contribution of the interactions of all of the components, as they occur over time. Therefore, the components must be considered as a collection (and not segregated into subgroups or classes) and the totality of the interactions of all the components is responsible for the global pattern. For direct processes, however, the pattern that one observes results more-or-less directly from the behavior of some subgroups of the components or a single component. This means that the behaviors of the components can be differentiated and the interactions of some components can be said to cause all or some aspects of the pattern. Therefore, the causal mechanisms responsible for the global patterns of emergent and direct processes are distinctly (perhaps ontologically) different.

The differences identified between these two kinds of flow processes in terms of the 10 attributes are based on the analyses of circulation and diffusion, plus a number of other examples. The proposal put forth here is by no means suggesting that these sets of 10 attributes are the only relevant ones discriminating direct from emergent processes; far from it. The suggesting is merely that for these two processes of flow that are commonly taught in middle school science, these two sets may be representative of two distinct kinds, thereby contributing toward the differential robustness of misconceptions. The next section considers whether students treat them as two different kinds or not.

THE NATURE OF STUDENTS' ALTERNATIVE CONCEPTIONS OF THE FLOW PROCESSES

In the literature, misconceptions have been identified for numerous concepts in the last couple of decades, and many of them have been shown to be extremely tenacious and robust, and they cannot be "removed" (in the sense of achieving deep and correct understanding) in spite of innovative instruction.[4] However, as shown earlier, some misconceptions are less robust, in that they can be corrected more successfully even with self-instruction (e.g., for concepts such as the circulatory system). In this section, misconceptions for these two processes of flow are first described, then their differences are characterized in ways that might cause differential learning.

Circulation: Alternative Conceptions

Several studies have identified students' misconceptions of circulation (Arnaudin & Mintzes, 1985; Catherall, 1981; Gellert, 1962). Perhaps the most useful data for our purpose is the work of Arnaudin and Mintzes (1985). They categorized multiple choice responses to six main questions, ranging from "What does the blood look like?" to "What path does the blood take when it leaves the heart?" Subjects ranged from 5th graders to college students.

Arnaudin and Mintzes (1985) gave explicit figures for the percentage of correct responses to three of their six questions. Question five is the most relevant

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[4] The use of the word "removed" is not meant to address the issue of whether misconceptions are forgotten, eliminated, or merely inhibited.

here, which asked “What path does blood take when it leaves the heart?” The most frequent choice (29–30%), among both 8th and 10th graders, is the heart-toe-heart path. Few students (less than 5%) at either grades subscribed to a double pattern of blood flow. For the other two questions, the correct responses ranged from less than 25% to 35%. Clearly the majority of students gave incorrect answers.

The heart-toe-heart path captured by Arnaudin & Mintzes’ Question five (1985) is similar to the flawed “single loop” conception (Chi, de Leeuw, et al., 1994) in that its assumptions about the three key ideas are diametrically opposed to the correct ideas (Chi, 2000b). First, the “single loop” conception does not assume that lungs are involved. Instead, they are assumed to be another body part to which blood has to travel. Second, it does not assume that the site of oxygen-carbon dioxide exchange is in the lungs; instead, it assumes such exchange happens in the heart. Third, it does not assume that there is a double loop. Instead, it assumes that the role of the circulatory system is a systemic one only. Therefore, one could claim that a flawed “single loop” conception is a coherent alternative theory, in that it is guided by an alternative set of three assumptions and it can be used consistently to provide explanations and answers to questions.

This “single loop” conception, based on the protocol provided earlier on the definition of *artery*, contains five constituent propositions:

1. Blood flows from the heart to the body in arteries.
2. Blood flows from the body to the heart in veins.
3. The body uses the “clean” blood in some way, rendering it unclean.
4. Blood is “cleaned” or “replenished with oxygen” in the heart.
5. Circulation is a cycle.

Although these propositions, when combined, formed a flawed mental model, each proposition is either true or can be corrected and elaborated so that it is true. In the context of the “double loop” model, propositions 1, 2, and 5 are all true. Proposition 3 needs to be elaborated in terms of what the mechanisms of “cleaning” and “replenishing with oxygen” are. Only Proposition 4 is false. But it is possible to correct that proposition by telling a student that blood is “cleaned” or “replenished with oxygen” not in the heart but in primarily the lungs. Earlier, we reported that 77% of 8th grade students’ incorrect propositions about the circulatory system can be corrected if the text addressed them, either directly or indirectly (de Leeuw, 1993; and also described in Chi & Roscoe, 2002).

In short, although students’ misconceptions of circulation are coherently flawed in that they might miss several correct propositions and the detailed mechanism and some propositions may be false, nevertheless, their misconceptions are not different *in kind* from the correct conception. That is, the alternative “single loop” model is of the same ontological kind as the “double loop” model. Therefore, a direct kind of process, such as circulation, is not misconceived in an ontological way. This would explain why their misconceptions were non-robust.

Diffusion: Alternative Conceptions

What exactly are students' misconceptions of diffusion? To characterize some of their misconceptions, several examples are taken from protocol data that we have collected (see Chi, et al., 1994), in which 8th grade students were given a passage to read about the circulatory system, taken from *Modern Biology*, the same text used by Marek (1986). The passage included discussion of gases and nutrients diffusing across the capillary walls and the diffusion of oxygen and carbon dioxide in the lungs. In addition, we supplemented this passage with another 12 sentences, discussing the diffusion of a cube of sugar in water.

Correctly explaining the initial and final conditions of the flow pattern and the cause–effect relations. If students are asked to explain what causes the flow pattern to arise, they tend to answer it in one of three correct ways: they either (a) describe the behavior of the components (e.g., *the dye water mixes with the clear water*), or appeal to (b) the initial conditions that caused the flow pattern to arise (e.g., *the concentration of dye in the two liquids are different*), or (c) the final conditions that caused the flow pattern to stop (e.g., *equilibrium, or when the dye is spread equally throughout the liquids*). For example, after the 8th graders read the passage, we asked them to explain *How might the exchange of oxygen and carbon dioxide take place in the lungs?* A student (Subject AFM) answered:

> Because with the oxygen…it diffuses into the bloodstream because there is a *greater concentration* in your lungs and a *lesser concentration* in the bloodstream, and just the opposite with carbon dioxide.

Therefore, clearly, they can give explanations of the conditions that trigger diffusion or flow. Citing the conditions is a type of explanations that is correct and adequate even in many work situations. Engineers can often operate with explanations of cause-and-effect relations (Miller, Streveler, Olds, & Nelson, 2003).

However, as mentioned earlier, such cause-and-effect relationship explanations fail to address the mechanism of *how* or *what causes* the flow pattern to arise; that is, what actually happens with the molecules that cause the flow pattern to be seen. To give a valid explanation of the causal mechanism (as opposed to a cause-and-effect relationship) requires that one specifies how the behavior of the components produced the pattern (Brewer, Chinn, & Samarapungavan, 2000; Machamer, Darden, & Craver, 2000). Therefore, to give a deep scientific causal explanation of some particular outcome amounts to citing the interactions leading up to the outcome (Salmon, 1989) and not merely the triggering conditions or the causal relationships between the conditions and the outcomes.

Incorrectly explaining the cause of the flow pattern at the constituent component level. If students had to answer more specifically the question of how the behaviors of the constituent components caused the flow pattern to arise, then their explanations are misconceived in several ways. A typical incorrect explanation misconceives of diffusion as two (or more) entities exchanging locations. For example, another 8th grade student (Subject AW) from the same study (Chi, 2000b, Chi, de Leeuw, et al., 1994), in answering the same question posed above, said:

> the capillaries that are in your lungs would…let *the oxygen come in* through the space in its walls *and then* the *carbon dioxide* would *go out*.

When pressed further with the query *Ok, and how come they go in and out?* The student further said:

> Well, because there's *it wants to get out* into a lower concentration, so *all the carbon dioxide* would *want to* go through so it would be in a lower concentration of them.

This misconception basically can be described as conceiving of diffusion as the orderly exchange in locations of oxygen and carbon dioxide and that such an exchange is intentional.

Superficially, this alternative conception can be characterized as one of an "intentional exchange". However, 5 constituent features are embedded in this "exchange" characterization. First, they think diffusion is a *sequential* process, in that first the oxygen comes in, "and then" the carbon dioxide would go out (see italicized segment of the quote above). Second, they refer to the "oxygen" and "carbon dioxide" as two separate *classes*, rather than treat all of them as a single collection of molecules. Third, they think of diffusion as an intentional process, as if the oxygen and the carbon dioxide have a *global goal* of wanting to go to an area of lower concentration. Fourth, they think of diffusion as a complete exchange process, in which "all" the oxygen ends up in one side and all the carbon dioxide would end up in another side of the capillary wall. In reality, the movement and location of the oxygen and carbon dioxide molecules can be *disjoint* from the appearance of exchange: That is, some oxygen and some carbon dioxide molecules can remain on its respective sides of the wall. Finally, they think the oxygen and carbon dioxide have *distinct* directed movements. The oxygen's movement is directed at entering ("come in") the lungs, whereas the carbon dioxide's movement is aimed at leaving ("go out") the lungs.

In short, it appears that this student's explanation contains many attributes of a direct process (at least our characterization of direct processes), rather than attributes of an emergent process. This then suggests that students' misunderstanding of emergent processes, such as diffusion, is based on their commonsense understanding of a direct kind of processes. Therefore, *emergent processes are misconceived of as a kind of direct processes*.

One might argue that the 5 attributes of a direct process, manifested in the above protocol snippet, is a function of the limitation of language. That is, it might be easier to talk about the movement of the oxygen and carbon dioxide in a *sequential* way, in that oxygen moves in first and then carbon dioxide moves out. But there is no reason why they cannot be discussed as both moving in and out at the same time. The language needed to reflect the ideas of emergent attributes are no more difficult than the language needed to describe the direct attributes. Hence, students' misconceived notions do not appear to be an artifact of language usage. Moreover, there are other ways to characterize the manifestation of differential attributes without using language.

Note that students' inability to explain at the constituent level is *not* due to their inability to reduce the components (blue and clear liquids) into its constituents (dye and water molecules). Rather, the problem is that they cannot release the class boundaries of the molecules of each component. That is, although they may understand and know that the dark liquid is composed of dye molecules and the clear liquid is composed of water molecules, they nevertheless fail to treat all the molecules (both the dye and water ones) as a collection. Instead, they continue to confine the dye and water molecules within the two separate class boundaries, corresponding to the two aggregate level components (dark and clear liquids). This idea will be further elaborated in the next section.

DISCUSSION

This article has provided a plausible explanation for why some science concepts are so robustly misconceived. Two science concepts of processes were analyzed, blood flow in the human circulatory system and diffusion of dye in water. Despite many superficial similarities, these two processes of flow can be characterized by two sets of mutually exclusive and diametrically opposite attributes, so that one could say that they are of different (ontological) kinds: diffusion is more like an emergent kind of processes whereas the circulatory system is more like a direct kind. However, it seems that students' commonsense ideas of processes correspond more closely to a direct kind of processes than an emergent kind. Therefore, they rely on their commonsense understanding of direct processes to interpret emergent ones. Assuming that learning is largely assimilating and integrating new information with existing knowledge (Chi & Ohlsson, in press), learning emergent kind of processes would cause misconceptions if students try to assimilate and interpret them as a kind of direct processes. This may explain the persistence of misconceptions. However, learning direct kind of processes should be less problematic, as seems to be true in the case of the circulatory system.

The proposal here is that students' misrepresentation of emergent-for-direct processes are skewed, in that they misrepresent emergent processes as a kind of direct ones (but not vice versa), which includes misrepresenting collections as classes. In short, I am not merely proposing that students conflate two kinds of processes. This skewed misrepresentation may have an innate source, in that even infants seem to understand direct kind of causality (Baillargeon, Kotovsky, Needlam, 1995; Gelman, 1998; Spelke, Phillips, & Woodward, 1995). This innate predisposition to interpret all processes as a direct kind may be another source for the robustness of misconceptions that makes them difficult to overcome.

The gist of the thesis for why students might have more difficulty learning diffusion than circulation is that they have misconceived of it as a kind of direct processes. Unfortunately, the examples chosen here—flow patterns in the circulatory system versus in diffusion, do have one crucial difference that might cause one to think that it is the underlying source of difference in the difficulty of learning one over the other. This difference is the fact that to understand diffusion, one must understand and focus on the behavior at the constituent level (the molecules), whereas in circulation, the behavior of the cells correspond to the behavior of the aggregate components, so that essentially one can explain the mechanism of flow and disregard the behavior at the cellular or tissue level. However, this difference is not the crucial feature that causes a differential explanation of the mechanism, for a couple of reasons. First, there are many other emergent processes that do not require the involvement of the constituent level in the explanation of the emergent mechanism. Several of these are described in Resnick (1994). Traffic jams, for example, is an emergent phenomenon. The uniform simultaneous interactions of the cars in a traffic flow can collectively lead to a jam. The components here are the cars and the pattern is the jam. Traffic jam satisfies all the attributes of an emergent process without going down to the constituent level. For example, the relationship between the cars and the jam is *disjoint* (Attribute 8 in Table 1), in that the jam can move backward while the cars move forward. The same is true for how termites build "giant mound-like nests rising more than ten feel tall" (Resnick, 1994, p. 75). Many examples in natural selection, such as how the giraffes' necks get longer over time, can all be explained by an emergent mechanism without resorting to a constituent level. Second, the constituent levels are involved in direct processes as well. As we saw in circulation, one could talk about the cells and tissues of each component. The point is that in this case of a direct process, the constituents at the cellular level interact in a *corresponding* way as the components (Attribute 8, Table 1), so that there is no need to differentiate the aggregate components from the constituent components for the purpose of explaining the pattern of flow. For example, neither the valves in the heart nor the valve tissue in the heart, interact with the valves or the valve tissues in the veins, whereas the dye molecules do interact randomly with water molecules. Therefore, it was necessary to discuss diffusion at the constituent level, primarily because that is where the interactions are *unconstrained* or *random* (Attribute 2, Table 1), whereas one can remain at the component level in the discussion of termites or traffic jam precisely because the *random interactions* of the collection occur at the level of the components (the cars, the termites). Therefore, the apparent blatant difference between circulation and diffusion is not a confounding explanation after all.

Because the goal of this article is merely to communicate the skeletal ideas of this explanation for why some misconceptions are robust and difficult to "remove," and because the ideas introduced here are still developing and speculative, several caveats are in order. Below, some background work and preliminary assumptions underlying this explanation are further discussed, some limitations are highlighted, comparison this explanation with alternative ideas are provided, and some instructional implications are addressed.

Background: A Question of Psychological Ontology

Studies that document the existence of misconceptions usually describe what students' naive conceptions are for a specific concept. For example, in physics, students' naïve conceptions of force are that it is a push or a pull (Minstrell & Stimpson, 1986), or that "continuing motion implies a continued force in the direction of the movement" (Clement, 1982). In chemistry, students misunderstand chemical reaction in thinking that a molecule of a compound consists of fragments that are glued together (e.g., H2O is H2 attached to O), rather than a process of bond breaking and bond formation (Ben-Zvi, Silberstein & Mamlok, 1989). Likewise, in our own example above, we could describe diffusion as being misconceived of as a process of exchanging places.

Besides knowing what students' misconceptions are for a variety of concepts, our work has concentrated on explaining what is the nature of these distinctly flawed conceptions. In our prior work, we had proposed a *domain-general* explanation for misconceptions, essentially suggesting that misconceptions derive from students' miscategorization of the concepts at the ontological level.

Our initial attempt at capturing the underlying structure of misconceptions was to suggest that students misrepresent certain concepts as a kind of *entity* (meaning here either substances or concrete objects), rather than as a kind of *process* (Chi, 1992; Chi & Slotta, 1993; Chi, Slotta & de Leeuw, 1994; Chi & Hausmann, 2003). For example, students tend to think of heat either as a kind of *substance* that objects may contain (e.g. hotness) or as a kind of *concrete objects* (e.g., heated molecules, both hotness and heated molecules are types of *entities*), rather than a *process* (of movement of atoms or molecules within an object). Similarly, students tend to treat forces as a kind of *substance* that can dissipate over time, much like the medieval notion of "impetus" (McCloskey, 1983), rather than a *process* of interactions. We have empirical evidence to support this type of miscategorization of processes-as-substance for concepts such as electrical current, heat transfer, and light (Slotta, Chi, & Joram, 1995).

Based on these notions, we postulated that conceptual change in these topics was difficult to achieve because it required students to "re-categorize" their conceptions from *entities* to *processes,* because entities and processes can be considered to be distinct ontological categories (Chi, 1992; 1997a; Sowa, 1995). Such re-categorization or re-representation can be viewed as a shift *across* ontological categories (Chi, 1992). Conceptual change that requires a shift across ontological categories was seen to be challenging and radical for a variety of reasons, such as a lack of awareness that such a shift is necessary, unfamiliarity with the target ontology, or the cognitive demand of re-inheriting all the attributes of a concept based on its new categorical membership. These various reasons have been discussed in Chi (1992; 1997a), Chi & Slotta (1993), and more recently in Chi and Roscoe (2002).

The main point of these early ideas, that students miscategorize certain science concepts as substances rather than processes, do not offer a complete account for concepts such as diffusion, for surely students know that diffusion is a *process*. Recall that students do in fact think of diffusion as a process of flow in which entities (such as dye liquid) move from one location to another. Therefore, a simple argument based on miscategorization of processes-as-substance is insufficient to explain the kind of misconceptions described in diffusion. But can we salvage the notion of ontological miscategorization to account for misconceptions? The nature of diffusion and circulation, as described above, can be taken to represent two different, perhaps ontologically distinct, kinds of processes: emergent and direct. Therefore, instead of misconceiving of processes-as-substance, perhaps students are misconceiving of emergent-as-a-direct kind of processes.

Assumption: Are Other Emergent Processes Robustly Misconceived?

If this explanation has any validity, then it ought to show that other robustly misconceived concepts are also of the emergent kind. That is, other robustly misconceived concepts ought to share the commonalities of emergent process attributes. One such example is the concepts of heat and temperature. Heat and temperature are badly confused, as has been described by Wiser and Carey (1983) and many others, to the extent that some researchers describe these topics as beyond the grasp of most 8th graders (Linn & Songer, 1993). Basically, students conflate heat and temperature, such that they would think of a metal bar with high temperature as one containing "hotness" or hot (i.e., heated) molecules, whereas a colder metal bar would be one that either has fewer heated molecules or has cold molecules.

Therefore, students think of temperature as measuring the amount of some *substance* (“hotness”) or concrete *objects* (heated molecules). A more accurate scientific view of temperature is concerned with the average speed or vibrational energy of the molecules within the metal bar, where molecules in a hotter bar vibrate faster (a *process)* than molecules in a colder bar. Therefore, in qualitative and laymen’s terms, temperature is more accurately thought of as a measure of the vibrational energy of molecules in a bar, whereas students conceptualize temperature as a measure of the amount of heated molecules or “hotness” (Reiner, et al., 2000). Therefore, it is accurate (but incomplete) to characterize students’ misconceptions as a mis-representation of process-as-a-substance.

It is incomplete to characterize misunderstanding of heat and temperature only as a mis-representation of process-as-substance because one further needs to explain how students conceive of heat transfer, as when a cold metal bar feels warmer after it came into contact with a hotter metal bar? They think of heat transfer as either hot particles moving from the hotter bar over to the cooler bar, or else as the two kinds of particles (hot and cold) exchanging places (analogous to the way students misconceive of diffusion). Further, this exchange or movement would terminate once equilibrium is reached (i.e., when the temperature of the two bars is the same). A more accurate explanation of heat transfer between two solids would not involve the transfer of any particles or atom, which are held rigidly in an atomic lattice. Rather, the initially disparate vibrational energy of adjacent metal atoms would gradually become equal between and within the two bars. The faster vibrating atoms would eventually impart some of their energy to the slower vibrating ones (so that the slower ones would vibrate faster, and the faster ones would vibrate slower), resulting in an eventual transfer of heat throughout the two bar system. An important point is that the atoms within the two bars will continue to jostle each other even after equilibrium is achieved.

In short, without going into greater detail, heat transfer clearly embodies the attributes of an emergent process, and misconceptions of heat transfer clearly embody the features of a direct process. We propose that the same characterization of mis-categorization of emergent-for-direct processes can be offered for many other robustly misconceived concepts of processes, such as evaporation, electrical current, natural selection, and so forth.

Limitations

The conceptualization and explanations proposed in this article are comprehensive, but still incomplete in many ways. Below I will address some of the shortcomings that remain.

Need of empirical support. The explanation proposed here (that students misrepresent an emergent kind of processes as a direct kind) needs to be validated with empirical evidence. One way to substantiate this claim is to see whether students' naïve explanations of emergent processes have the characteristic attributes of direct processes, and whether their post-instructional explanations then have the characteristic attributes of an emergent process.

We have not yet undertaken systematic empirical work to support the claim in this article, as we have done in the case of misrepresenting processes-as-substance (see Slotta, et al., 1995; and Slotta & Chi, in press). As noted earlier, one method of verifying that students misconceive of concepts such as force and heat as a substance rather than a process, is to code their *predicate usage* manifested in their explanations for problems involving these concepts. The same kind of coding scheme can be used here, with predicates referring to either direct or emergent attributes. (A preliminary attempt of this coding scheme was undertaken by Ferrari & Chi, 1998. Moreover, one can also code their *referential usage* to discriminate whether they treat the components as classes of objects or a collection of objects.)

A commonsense characterization of direct causal processes. Direct kinds of causal processes have been described in great length in both the philosophy (Hume, 1960; Glymour, 1998) and psychology literature (Cheng & Novick,1991; Wilson & Keil, 2000). A fundamental question asked by the psychological and philosophical literature about direct processes is how people infer causes. For example, when we see a boy kick a ball and then the ball hitting and breaking a window, we intuitively attribute the boy to be the causal agent, the window to be the recipient, and the kicked ball as the instrument that causes the broken window. Causes are inferred from features such as (a) contiguity between the presumed cause (the boy) and the observed effect (broken window), if the cause precedes the effect or (b) spatial contiguity, if the cause had to be present whenever the effect was obtained, or if the two events (boy kicking) and (window breaking) share some similarity in characteristics (such as the direction in which the glass breaks and the direction the ball is moving). Therefore, the kind of features psychologists and philosophers discuss about how causes are inferred are similar (but perhaps do not correspond completely) to the kind of attributes specified here in Table 1 about the nature of direct causal processes. Moreover, causal processes are usually discussed as one level, and seldom as two or more levels.

The direct causal process attributes listed in Table 1 were derived from analyses of a few every day processes and a few processes introduced in middle school texts. The analyses were also guided by students' misunderstanding as indicated in the literature. Needless to say, there are numerous more complicated direct causal processes that could have been analyzed (Perkins and Grotzer, 2000). Therefore, I am definitely not claiming that the attributes of direct processes that have been identified here are the exhaustive or necessary ones. The goal here was merely to identify a minimal set of attributes that seem to differentiate direct from emergent processes, and to propose them as people's commonsense notions of causal processes.

Relation to complex dynamic systems. During the last decade, there has been burgeoning interest in nonlinear complex dynamic processes (Casti, 1994; Holland, 1998; Prigogine & Stengers, 1984). A nonlinear complex dynamic system can be characterized as a system of numerous individual agents (or elements) whose independent interactions result in emergent and complex behavior not exhibited at the level of the individual elements. In the natural science literature, one might also refer to this kind of phenomena as self-organization, in which macroscopic order emerges spontaneously without plan, algorithm, or control structure. (See van der Maas, 1995; and Lewis & Granic, 1999 for terminology usage.) Examples of complex dynamic processes include: eco-processes, fractals, laser beams, heart rhythms, and weather patterns. Complex dynamic processes thus appear to be a unifying cross-disciplinary construct.

Nonlinear complex dynamic processes are investigated mostly by physicists and mathematicians, who are interested in understanding (and modeling) how complex coherent orderly forms (such as the formation of galaxies or the formation of snow flakes, Casti, 1994; Holland, 1998; Prigogine & Stengers, 1984) emerge from recursive interactions among simpler components. Their efforts have been focused on trying to see if they can model and predict the emergent phenomena, using very complicated mathematics and modeling tools such as cellular automata, genetic algorithms, classifier processes, and neural networks. A group of social scientists are also exploring the extent to which many other phenomena are complex dynamic processes. For example, Thelan and Smith (1994) propose that human development can be modeled as a complex dynamic system. Others propose that neural development is also a complex dynamic system (Edelman, 1987).

The kind of emergent processes covered in the middle school curricula and described in this article may resemble some type of complex dynamic processes. They do differ, however, in the predictability and computability of how the pattern level emerges. For the kind of emergent processes discussed in the middle school texts, one can calculate the pattern level behavior by a simple computation of either the collective sum (i.e., the net effect), some statistical average, or a proportion/distribution of the collection when given the initial conditions, whereas scientists have yet been able to compute and predict the emergence of nonlinear complex dynamic processes.

However, I cannot offer a deep scientific comparison between emergent processes of the kind described here and other kinds, such as nonlinear complex dynamic processes. The focus here is not on the scientific similarity or dissimilarity between these two types of emergent processes, nor am I sufficiently informed about them to make such comparisons. Rather, the goal here is to understand the nature of students' misconceptions of one of these kinds of emergent processes, in the interest of knowing how such misconceptions can be overcome to facilitate deep understanding. Besides the theoretical analyses offered in this article, another approach to achieve the same goal of understanding students' misconceptions of emergent processes is to contrast the ways that experts and novices solve problems dealing with complex systems (Engle & Chi, 2002; Jacobson, 2001).

In short, emergent processes or emergent-like processes (such as complex dynamic systems) and direct causal processes have been investigated extensively by physical scientists, social scientists, psychologists, and philosophers. However, each group of researchers is asking a different set of questions. The question this article addresses is *how and why* students have difficulty understanding a much simpler kind of emergent processes, those that scientists already understand. The answer proposes the specification of an underlying domain-general ontological category of emergent processes in terms of a set of attributes, and suggests that understanding this ontological category may provide a conceptual structure to which one can embed and interpret emergent processes. The assumption is that students fail to understand even these much simpler kind of emergent processes, because these processes have been misinterpreted as a direct kind of causal processes.

Contrast With Alternative Explanations

The explanation provided here is not sufficiently developed nor validated to offer a deep contrast with alternative explanations, although shallow contrasts can be made. This explanation views misconceptions as a *domain-general* misinterpretation of one kind of processes for another kind. This kind of misinterpretation can occur for numerous concepts across many domains.

As pointed out earlier, the alternative views in the literature are *domain-specific* ones. There is not enough evidence at this point to discriminate whether one or another view is correct. They could both be correct in the sense that they are providing explanations at different levels, in the same way that students' macro level explanations of emergent processes are correct even though there is a deeper correct micro-level explanation.

Aside from the futility at this point of making this kind of comparative statements, a critical question to ask is how can our domain-general view account for the variability and fragmented nature of misconceptions? This diversity and apparent fragmented nature can be accounted for in the following simple way. Any naïve explanation can appeal to a number of the attributes of a direct process. An appeal to any one of the 10 or so attributes (or any combination there of) can produce an exponentially large number of incorrect explanations that differ in surface forms, appearing to be idiosyncratic and fragmented, even though they were generated from a systematic appeal to the ontological attributes of a commonsense direct process. Although the fourth section of this article, showing students' alternative conceptions, gives a flavor of the superficial fragmented nature of misconceptions, a complete analyses of protocols to demonstrate this interpretation cannot be presented here.

Comparison With Other Instructional Approaches and Implications

The analyses presented here suggest that some concepts (of processes) ought to be more readily learned than others, and this differentiation is based on whether the to-be-learned concept has been mis-represented or not. When the to-be-learned concept is categorized correctly (as in the case of circulation), then students' misconceptions, whether they are coherent and theory-like or fragment ed and piecemeal, can be modified through common learning processes such as deletion, addition, and refinement of existing propositions or beliefs. These self-repair processes (Chi, 2000b) can correct nonrobust misconceptions with standard kinds of instructional intervention and sometimes even with just self-directed instruction, because the correction is undertaken *within* an ontological category. However, when the to-be-learned concept is ontologically mis-categorized (as in the case of diffusion), then learning and instruction may require at least two additional processes. First, students have to be made aware that they need to shift their representation of the to-be-learned concept from one ontological structure to another. Second, the schema or structure to which they have to shift their representation, the emergent process schema, may not already exist. This means that instruction has to focus on helping students build such a schema first. Therefore, instructional intervention for robustly misconceived concepts of the emergent kind may require attention to these two additional learning processes: building and ontological shifting.

Many other researchers have recognized directly that emergent processes, such as how ants find and collect their food (Resnick, 1994; Wilensky & Reisman, in press), are difficult to understand. Therefore, their goal is to assert directly that emergent kind of processes are difficult to learn, and propose ways of overcoming this difficulty in understanding emergent processes. Our goal is complementary; we want to propose why emergent processes are difficult to understand, in the context of the existence of rampant robust misconceptions. Our explanation focused on identifying a common underlying structure for emergent processes and postulate how it differs ontologically from a direct process structure.

The differences in our goals and explanations for why emergent processes are difficult to learn also imply differences in how we might approach instruction. Their approach to promoting students' understanding of various emergent processes is to try various innovative instructional intervention such as by engaging students in explorations of computer and participatory simulations (Colella, 2000), as well as role-playing activities that model emergent processes (Resnick & Wilensky, 1998), and so forth (Penner, 2000; Resnick , 1994; 1996; Resnick and Wilensky, 1998; and Wilensky, 1995; Wilensky & Reisman, in press; Wilensky &

Resnick, 1999). These approaches focus on learning specific emergent processes directly. Our approach, based on our proposed explanation, would be to focus on teaching the underlying causal structure of emergent processes via the ontological attributes. The idea is that if we can help students build a general structure or schema of emergence first (in the context of using simulations and role-playing activities), then presumably learning, in the sense of assimilating and integrating new knowledge with existing knowledge, can be more easily undertaken because the relevant cognitive structure will already have existed. Moreover, presumably such learning can transfer more readily because the attributes of an emergent schema will apply to many emergent processes. However, these are speculative ideas and it is premature to foreshadow these findings at this point.

In conclusion, the ideas presented in this article offer a speculative and incomplete alternative account of the persistence and robustness of misconceptions for many science concepts. However, because this account is alternative and domain-general, its validity might be worth pursuing in the hopes of designing instruction that can foster deeper and generalizable understanding of science.

ACKNOWLEDGMENTS

I am grateful for funding provided by the Spencer Foundation (Grant 200100305).

Ideas from an earlier manuscript were first presented at the meeting of the American Educational Research Association, April, 2000 and elaborated on at the meeting of the American Educational Research Association, April, 2001.

I greatly appreciate the thoughtful comments provided by Andi DiSessa, Randi Engle, James Greeno, Grame Halford, Janet Kolodner, Rod Roscoe, Marguerite Roy, Jim Slotta, and Kurt VanLehn; as well as several anonymous reviewers.

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APPENDIX

More Detailed Explanation of How the Flow Pattern Arises in Diffusion

To be more concrete, suppose we examine two successive slices of the tube at a moment of time (see Figure 2). The proportion of dye molecules determines the color of the liquid in each slice. Calculating the proportion requires summing *all* the dye and water molecules in the collection. Let's say the proportion of the dye molecules (the dark color dots) is 100% for the first slice and 73% for the second slice, at a given instance of time, let's say at Time1as shown in the upper panel of Figure 2. That is, the upper panel of Figure 2 shows the static pattern at Time 1, in which the first slice looks bluer than the second slice, and the second slice looks bluer than the third slice. At Time 2, looking at those same three slices, the proportion of dye molecules for the first slice might have decreased to 87%, but the proportion of the dye molecules in the second slice might have increased to 81%, and so on, as shown in Figure 2. This means that at Time 2, the static pattern shows the second slice to look bluer than it had before at Time 1. In general, *at any moment of time*, each successive slice would likely (but not necessarily) contain a different proportion of dye and water molecules, usually with a decreasing number of dye molecules in each successive slice (because it takes time for the dye molecules to bounce further and further from their original locations). *Over time* (i.e, from Time

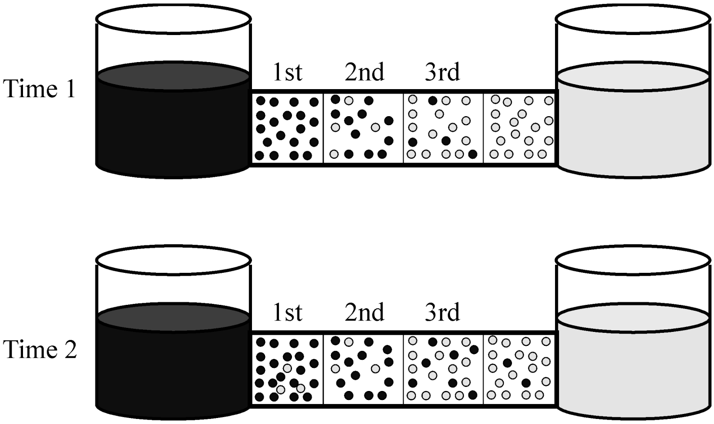

FIGURE 2 Details of the behavior of the molecules over time in diffusion of liquids.

1 to Time 2), the pattern *changes*, in that each successive slice would get more and more dye molecules, so that the dynamic pattern one perceives is that of a flow.

Therefore, this orderly perceptual pattern of flow at the macro level is simply the changing patterns of the collections of the behavior of all the molecules at each instance of time. No single interaction of the dye and water molecules is responsible for the observed flow; nor are the interactions of a class of m interactions of a class of molecules (such as the dyed ones) alone responsible. That is, it is not the case that all of the dye molecules (a class of molecules) move in one direction, toward the clear water (the other class) of molecules. The dye molecules do not share a set of behaviors (e.g., flowing to the right) that is distinct from the behavior of the water molecules, so that they should not be treated as separate classes of objects. Rather, both the dye and the water molecules should be considered as a collection.