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Misunderstanding Emergent Causal Mechanism in Natural Selection

Michelene T. H. Chi,
Agnieszka Kosminska Kristensen,
and Rod Roscoe

This chapter provides a theoretical account for why many science concepts, especially those for which students have deeply held misconceptions (e.g., natural selection), are so difficult to learn. In a nutshell, the theory postulates that the various phenomena (or concepts and processes) young students encounter in their daily environment help them build an internal structure (that we will call a Direct Causal Schema) that allows them to interpret and understand new phenomena that they have to learn in school. Our theory presupposes that learning of new information involves assimilating it into a relevant schema. Because young students have developed a Direct Causal Schema from their daily experiences, when they encounter new phenomena, they activate their Direct Causal Schema to interpret the new phenomena. However, many phenomena that students have to learn in school should not be assimilated into a Direct Causal Schema; instead, they should be assimilated into an alternative schema (that we will call an Emergent Causal Schema). Therefore, they are activating an inappropriate schema (the Direct Causal Schema) and assimilating new phenomena into it, resulting in robust and tenacious misconceptions.

The development of this theoretical account for misconceptions in science was first introduced in Chi (1992). Over the years, it has evolved from a consideration of static concepts, such as *heat*, to process concepts, such as *heat transfer* (see for example, Chi, Slotta, & de Leeuw, 1994; Chi, 1997; Slotta, Chi, & Joram, 1995; Chi & Roscoe, 2002; Chi, 2005; Slotta & Chi, 2006), as well as consideration of other related issues, such as whether ontological shift underlies important scientific discoveries (Chi & Hausmann, 2003). The version of the theory presented in this chapter improves the previously framed theory in Chi (2005) in ways that will be pointed out. Moreover, this chapter instantiates the theory with an example in a biological context (the concept of natural selection), whereas the previous study

(Chi, 2005) instantiated the theory in a chemical domain (the concept of diffusion). Instantiation in two different domains illustrates the generality of this theoretical account.

Below, we first present our notions of learning via assimilation, in order to see what aspects of the assimilation process might cause misconceptions of a robust and tenacious magnitude. We then expand on notions of schemas and mis-activation, describe characteristic "attributes" and "features" of a Direct and an Emergent Causal Schema, and exemplify how direct attributes and features are used to generate explanations of natural selection incorrectly. We end with description of a very preliminary pilot study that tests this theory's prescription for instruction.

A Brief Cognitive Account of Learning via Assimilation

Fundamentally, learning occurs via assimilation (Chi & Ohlsson, 2005), which means that we assimilate new to-be-learned information in the context of what we already know. This suggests that assimilation can be decomposed into at least three processes: *activation*, *integration*, and *repair*. For a school-age child to learn and understand a new phenomenon or a new concept, the child must bring what relevant knowledge s/he has to bear on this understanding. For example, suppose a child had to learn the new information that a *Tyrannosaurus Rex has "sharp teeth."* In order to learn this piece of new information, the child may use the "sharp teeth" feature to activate a meat-eating schema, assuming that she knows that *meat-eaters have sharp teeth.* Once activated, she can integrate Tyrannosaurs into her meat-eating schema (e.g., instantiate it as an instance of meat-eaters), and further infer, using knowledge in that schema, that meat-eaters tend to be massive, and likely to live on land as opposed to hiding in the swamp, as plant-eaters like to do. Thus, she can rely on the knowledge embedded in her meat-eating schema to reason, explain, predict, create expectations, and so forth, about Tyrannosaurs (Chi, Hutchinson & Robin, 1989; Chi & Koeske, 1983; Gobbo & Chi, 1986).

This simplistic example illustrates the commonly accepted assumption that in learning and understanding instruction, students *assimilate* the to-be-learned information in the context of what they know, and that their prior knowledge is often organized in some coherent form such as a schema. Thus, in the situation depicted above, inferring that a Tyrannosaurus Rex is a meat-eater because it has "sharp teeth" requires *activating* prior knowledge followed by *integrating* the new information with the activated meat-eating schema. If we then further tell the child some other new information about Tyrannosaurs, such as that *they will eat a plant-eater dinosaur but will never be eaten by a plant-eater*, the child may have to edit or change her knowledge if she had originally believed that *plant-eaters can also eat meat-eaters.* Thus, *repair* can be conceived of as the process of editing existing knowledge based on new information (Chi, 2000). Below, we describe each of the three subprocesses of assimilation (activation, integration, and repair), focusing on how each subprocess might normally proceed, and also on how it can go wrong, to indicate whether such failures can cause misconceptions of the robust and tenacious kind.

ACTIVATION

Activation of prior knowledge in the form of schema (if the knowledge is coherently organized), on the surface, seems to be a straightforward process with few opportunities for incorrect activation. For example, if I am telling you about someone going to a restaurant, you can readily activate and retrieve your "restaurant script" to interpret and understand what I am talking about. However, activation of prior schema can go wrong in at least five different ways that have been studied in the literature, causing misunderstanding. We describe each below.

Failure to Activate a Schema Due to Insufficient Cues

One way that misunderstanding can occur is when no relevant prior knowledge or schema is activated at all. This is the case in which one can read and understand each sentence in a paragraph, but the paragraph as a whole makes no sense. For example, college students could not understand a well-written but seemingly vague paragraph about washing clothes until they were told in advance that the paragraph was about laundry, thus allowing them to activate their "laundry" schema so they could interpret the clothes-washing sentences (Bransford & Johnson, 1972). Similarly, adults could not determine whether the conclusion of a logic problem was valid unless they were cued to activate their "permission" schema that embodied an implicit set of logical rules (Cheng & Holyoak, 1985). These two studies exemplify the situation in which people did not know what schema to activate until the cues in the problem statements were made more explicit. Once the cues were made more explicit, such as through an advance organizer or a familiar context, people could activate the relevant schema; the sentences about laundry could be understood and the problem about permission could be solved because they could now be interpreted in terms of the activated schemas. Note that in these two examples, not only do people already have the relevant schemas of "laundry" and "permission," but these schemas are likely to be well developed. As adults, they have probably had many opportunities to do laundry and to give or get permission.

Activating an Underdeveloped Schema

A second way in which students can have difficulty learning (e.g., to solve problems correctly) is the case of activating an underdeveloped schema. Without experiences, schemas can be underdeveloped, sparse, with much knowledge missing. Underdeveloped schemas are revealed most readily when one contrasts the knowledge of novices with experts. Experts, for example, can solve textbook physics problems easily because they can bring to bear their well-developed problem schemas, so that these problems are merely routine applications of what they know.

The same textbook problems become nonroutine problems for novices since they have only rudimentary and incomplete schemas for these problems (Chi, Feltovich, & Glaser, 1981). Underdeveloped schemas can be remediated by acquiring more skills or expertise.

Activating an Inappropriate Schema without Awareness When an Appropriate One Is Available.

A third way that people can fail to correctly understand new information is when an inappropriate schema is activated even though an appropriate one is available. For example, when young children see a creature swimming in water that has fins, looks elliptical, does not have arms or legs, they can correctly identify that object as a *fish*. However, when they see another elliptical object swimming in the water with fins, they might also identify it as a *fish* when in fact it's a *mammal* because it is a whale. Philosophers refer to this kind of error as a *category mistake.* One can easily understand how such a mistake can be made: basically the features of a whale look like features of a *fish* such as a shark. However, such a mistake can often be easily remedied by direct instruction, such as through refutation (Kowalski & Taylor, 2009). We can simply tell a child that this whale is not a *fish*, but is a kind of *mammal* because like other *mammals*, it breathes air, and we can point to a feature (or several features) such as the blow-hole that differentiates this fish-like creature from other *fish*.

This category mistake is easy to remediate for two reasons: first, there are salient features that differentiate *fish* from *mammals*; and second, *mammals* presumably is a category that children already know something about, so that blow-hole or other salient features (e.g., bearing live young) are already in the child's *mammal* category. For these two reasons, children's category mistakes in the case of misidentifying a mammal-for-a-fish can be corrected when they are told that a fish-like mammal, called a whale, exists. A child will accept this explanation since she already knows about *mammals*, and knows that some *mammals* breathe through blow-holes. Thus, this type of misconception can be readily removed, by changing the link between a concept and its category, from one familiar category to another familiar category (Chi, 2008).

One can intentionally manipulate the activation of an inappropriate schema in an experimental study, as in the case of asking students to read the same passage from either the perspective of a "burglar" or the perspective of a "home-buyer" (Pichert & Anderson, 1977). This study found that learning and recall of important ideas within a story depended on the perspective that was taken. However, usually we assume that activating an inappropriate schema is caused by misleading features and cues.

Activating an Inappropriate Schema with Awareness That an Appropriate One Is Missing

In the above case, an individual activated an inappropriate schema even though an appropriate one was available. Activation of an inappropriate schema can also occur when an appropriate one is missing and the learner knows it is missing. This case happens often. For example, if we are reading letters describing a wedding in the United States and one in India, not only are we better at recalling more information from the letters about an American wedding than an Indian wedding (Steffensen, Joag-Dev, & Anderson, 1979), but we are quite aware that we do not know much about an Indian wedding. Our misunderstanding of an Indian wedding is caused by our use of an American wedding schema to interpret an Indian wedding (e.g., perhaps using analogical reasoning). To improve our understanding of an Indian wedding, we can specifically develop our schema of Indian weddings.

Activating an Inappropriate Schema without Awareness That an Appropriate One Is Missing (Mis-activation).

The fifth case, one that is our proposed account, corresponds to activating an inappropriate schema when an appropriate one is missing, and moreover, the learner is not aware that an inappropriate one is being activated and that an appropriate one is not available. Our conjecture is that the lack of awareness and the lack of an appropriate schema are the fundamental causes of robust and tenacious misconceptions. The rest of this chapter unpacks this premise, but we first complete our description of the other two subprocesses: integration and repair.

INTEGRATION AND REPAIR

The processes of correctly integrating new to-be-learned information with an activated schema or prior knowledge and repairing existing information with new information can result in both enrichment of one's schema (in the sense of adding more details and making it more complete) and accommodation (in the sense of modifying the structure of an existing schema). Enrichment and accommodation can be seen more clearly in the context of a mental model representation, as shown in the following example. Many students' naive conception of the human circulatory system is a single-loop model with no lungs. In such a single-loop mental model, blood carrying oxygen flows to all parts of the body, then returns to the heart. The implicit assumption is that the heart oxygenates blood, and the lungs play no obvious role in circulation, even though all students know that inhaled air containing oxygen enters the lungs. By telling students who possess a naive single-loop mental model (or asking them to read) various facts about the circulatory system, such as that *the septum divides the heart lengthwise into two sides*, and *the right side pumps blood to the lungs and the left side pumps blood to other parts of the body*, and so forth, students can integrate these facts with their initial single-loop model. Besides integration, other incoming new information can cause repairs, consisting of deletion and substitution. For example, suppose a student initially thought that the *human heart has two chambers*, and then was told that *the human heart has four chambers*; such refutation can allow the learner to repair or edit her original belief. Thus, after many integrations and repairs, a student's naive single-loop model can be enriched and eventually becomes the correct double-loop model

(Chi, de Leeuw, Chiu, & LaVancher, 1994). Thus, holding a naive single-loop model does not constitute a robust misconception.

In this case, by enriching through correct integration and repairs, the structure of the mental model also has changed, from a single-loop to a double-loop. We can define structural changes in many ways, such as by differences in the fundamental assumptions underlying each type of model (e.g., the assumption about which organs, lungs or heart, are responsible for oxygenation). Thus, through assimilation (activation, integration, and repair), accommodation (or changes in the structure of their mental model) can result.

However, assimilation does not always occur correctly. Aside from failures due to incorrect activation of a relevant schema, failures can also be attributed to the integration/repair processes. In the example above, when students with a single-loop model read the sentence *The right side pumps blood to the lungs and the left side pumps blood to other parts of the body,* they may misinterpret the implication of the role of lungs in this sentence and assume that blood goes to the lungs because lungs are a part of the body and blood has to go to all parts of the body. Thus, *blood going to the lungs* is simply integrated as a refinement or detail of *blood going to all parts of the body*, rather than repairing the incorrect knowledge that the *heart oxygenates blood* to the correct knowledge that the *lungs oxygenate blood*. This type of incorrect integration and failure to repair will not result in correctaccommodation. Vosniadou and Brewer (1992) have similar evidence showing that when young children, whose naive mental models of the earth are a flat square, were told that *the earth is round*, they integrated this information incorrectly by changing their flat square earth to a round pancake earth. In these examples, failure to understand refers to the processes of incorrect *integration* and failure to *repair*, even when the relevant and appropriate schema (a single-loop model or earth model) is *activated*.

While we do not fully understand when and why integration and repair are sometimes faulty, on many occasions, the mis-integration makes sense. For example, when a child has a square and flat initial conception of earth, it is not difficult to see how telling the child that *the earth is round* can be integrated erroneously, since *round* can be thought of in a unidimensional sense (pancake) or a three-dimensional sense (globe). Similarly with the example of *blood going to the lungs*: There is no reason that a learner with a naive single-loop mental model might think of other reasons for blood to go to the lungs, until further information is provided. One way that we might make students integrate and repair their knowledge correctly is to make them reflect on their integration and need for repair (Chi, 2000).

In sum, there are numerous reasons for why and how new information can be misunderstood: either an inappropriate schema can be activated, or it can be incorrectly integrated, or it was not used to repair incorrect existing knowledge. In many cases, when incorrect knowledge and ideas exist, conceptual change can still be achieved, as we indicated in the discussion above. The difficulty in learning and understanding many science concepts, however, is not one of incorrect activation due to insufficient cues or underdeveloped schema, nor one of activating an inappropriate schema without awareness that a more relevant one is available, nor one of activating an inappropriate schema with awareness that a relevant one is missing, nor is it due to incorrect integration/repair. Instead, the problem, we propose, is one of mistakenly activating a well-developed schema that is inappropriate for interpreting the to-be-learned new science concepts, and moreover, this is done without awareness that the appropriate schema is missing. We refer to this problem as *mis-activation*. This can lead to seriously flawed and robust deep explanations.

Mis-activation

In our everyday encounters with events and phenomena in the real world, we build up understanding and linkages between what we perceive and how we conceive of it. There is a vast psychological literature on concepts and categorization, showing that humans can learn to identify the salient features of a concept, and based on those features, they can categorize it correctly using several plausible mechanisms, such as comparing the features to a prototype. This paper is not concerned with the exact mechanism of this categorization process, nor the features that are used for such categorization. The point is simply to note that humans can do this correctly and seemingly effortlessly, and categorization can be conceived of as a process of activation.

How does mis-activation happen and when does it occur? One possible reason why an inappropriate schema is activated is that the perceptual cues in the new to-be-learned phenomenon look similar to the cues of phenomena relevant to the activated schema (as in the case of *whale*). Thus, an inappropriate schema is activated because of misleading cues. Such inappropriate activation is usually done even without awareness that it is incorrect (Chi & Hausmann, 2003; Chi & Roscoe, 2002) because the appropriate schema may be entirely missing. Thus, the central theoretical account we propose for the failures of learning many science concepts is the problem of activating an inappropriate schema without awareness because the appropriate schema is missing.

This mis-activation account suggests that misunderstanding of science concepts can be remediated by instruction that attempts to help learners *build* and establish a relevant but missing schema, and to *differentiate* the cues with respect to when such a schema needs to be activated. But before proceeding with an instructional intervention proposal, additional challenges need to be addressed. First and foremost, what relevant schema is missing and needed for understanding many science concepts? Second, how do we overcome the problem of the "learning paradox?" The "learning paradox," a term coined by Bereiter (1985), can be interpreted in our context to state that if all new information is always learned by assimilating it into existing schemas, then how can we ever learn truly new information, or information that does not fit with any of our existing schemas? In this paper, we first explain what relevant schema is missing, and how we can help students avoid inappropriate activation and develop a new relevant schema to overcome the learning paradox.

But for what concepts would we *not* have a schema, since schemas are built up from our everyday experiences? In order to answer this question, we begin by analyzing the kind of schema that children do have (that we refer to as a Direct Causal Schema), for process concepts. We focus on *process* concepts because robust misconceptions tend to be about processes, such as electrical current, forces, sinking-and-floating, natural selection, and so forth.

In the following section, we (1) define the components of a process; (2) identify the characteristic "attributes" of sequential processes that help students build up a Direct Causal Schema for interpreting them; (3) show how such a Direct Causal Schema cannot be used to explain nonsequential processes; (4) show that when it is used to explain a nonsequential process, it generates robust misconceived explanations; (5) describe the attributes of an emergent explanation for nonsequential processes; and (6) explain its relationships to understanding the Darwinian principles.

Processes

What is a process? Cognitive scientists have rarely studied process concepts. The lion's share of the studies focuses on taxonomic concepts (see reviews by Smith, 1989). Processes have only been defined broadly, as "a series of actions or operations conducing to an end" (Webster's dictionary), such as a baseball game, birds flocking together, blood circulating throughout our body, and hot air flowing into a colder room. However, we have analyzed and decomposed processes into four components.

First, a process is usually composed of *agents*, which can be animate or inanimate. The agents of a baseball game, obviously, are the animate players and the inanimate objects (such as the bases, the bats, etc). For simplicity, the examples in this paper will refer primarily to the animate *agents*. Agents can cohere into *subgroups*, usually on the basis of perceptual similarity. For example, in a baseball game, all the players (agents) form teams (subgroups), and members of a team can usually be detected by the color of their uniform. Agents also *interact*. In a baseball game, the pitcher interacts with the batter when the pitcher pitches the ball and the batter swings at it.

Agents of a process interact to form *patterns*. The *pattern* of a process refers to the activities of all the agents. The pattern that is captured at any moment in time (like a snapshot) can be referred to as a static pattern. A static pattern in a baseball game, for example, may show the distribution of players on the bases, the score on the board, and so forth. Patterns may sometimes appear static even though the agents are dynamic. For example, a flock of geese flying in a V-formation may appear static in that the same V-pattern is seen from one instant to another, but the agents are dynamic in that each goose is flying behind another goose. This is why it is important to discriminate between the pattern and the agent levels.

Patterns can change over time, and the changing patterns can be referred to as dynamic patterns, consisting of the changing players on different bases, the changing score, and so forth. Thus, common dynamic patterns consist of changes in locations, and increases or decreases in color, size, speed, or quantity. The term *pattern* will be used as a general term to include both static and dynamic patterns at the pattern level (and not at the agent level).

Patterns are often visible, but they don't have to be, since they can be visualized or imagined as well. For example, without actually seeing it, one can visualize the pattern of a building getting taller from being built everyday. Thus, for any process, one could decompose it into several components: the *agents*, the *subgroup* of agents, *interactions* among the agents, and the *pattern.*

DEVELOPING A DIRECT CAUSAL SCHEMA FROM ENCOUNTERING EVERYDAY SEQUENTIAL PROCESSES

How do young children understand a sequential process such as a baseball game? What kind of a schema do they develop from understanding these kinds of processes? Although little research has been done on understanding processes, much work has been done on how young children comprehend stories and everyday events, such as going to a restaurant. The upshot of many classic papers on this topic is that from repeated exposures to stories and everyday events, children form internal structures such as *narrative schemas* and *scripts* (Rumelhart, 1977; Stein & Glenn, 1979; Bower & Black, 1980; Mandler & Johnson, 1977). These narrative schemas and scripts share many characteristics, with components such as having "a central character" or a protagonist, who decides to undertake "a sequence of actions or interactions." These sequences of interactions are logically related with "causal" or "enabling" relations, carried out in the pursuit of attaining "a global goal." When the goal is attained, then the story concludes and the interactions "terminate." Thus, children's experiences with stories and going to restaurants allow them to develop a *narrative* schema and *restaurant scripts.*

We assume that children use a schema very similar to a narrative schema to understand everyday events such as a baseball game. For instance, in baseball, there is a "central character" such as the pitcher, who causes "a series of interactions" to occur (pitching, running, throwing), in trying to attain "the local goal" of getting onto first base, with the intention of achieving "the global goal" of winning, and when the global goal is attained, then the interactions "terminate" because the game is over. Thus, understanding a baseball game is not unlike understanding many narrative stories that children read.

Many of the processes that children might encounter in their everyday environment, such as wolves hunting prey (that they might see on the Discovery Channel), or a skyscraper getting taller everyday from being built by workers, might be termed "sequential processes." We put quotes on the terms "sequential processes" because these are not technical or scientific terms, but merely terms we define. By analyzing several different everyday sequential processes, we derived characteristics that seem to be common to most of them (Chi, 2005; Chi, Roscoe, Slotta, Roy & Chase, under revision). This derivation procedure was carried out by expanding and translating the common characteristics of narrative schema and scripts into generalized and qualitative terms. For example, instead of describing the central character of a story as "the protagonist," we translated and generalized it into *an agent with a special status*. By doing so, we derived common characteristics that may be shared across many processes.

CAPTURING THE CHARACTERISTIC "ATTRIBUTES" IN CAUSAL EXPLANATIONS FOR EVERYDAY PATTERNS

Patterns of processes often require explanations. For a baseball game, for instance, one often asks questions such as *Why did this team win?*, *Why were there so many innings played?*, and so forth. The explanations can be characterized in half-a-dozen ways. The first way is to point to a *single* individual or a *subgroup* of individuals as the causal agents. If the pattern in a baseball game to be explained is a home run, an explanation might point to the interaction of a single agent, such as a good swing by the batter or the near-miss catch by the outfielder. Sometimes the interactions of multiple causal agents, or a *subgroup of agents* are cited as explanations. In a football game, not only is the quarterback responsible, but sometimes the entire subgroup of the "receivers" might be deemed as facilitating or detrimental to winning a game. Children and adults seem predisposed to this kind of teleological explanation attributing causes to a *single* agent or a *subgroup* of agents.

Because the causal explanation often refers to a single or a subgroup of identifiable individuals, these individuals have *differential* or *special status* from the rest of the individuals participating in the process. In a baseball game, the pitcher's performance is often singled out as making or breaking a game. Thus, a second way to characterize explanations of processes is that different individuals have different status of importance toward producing a pattern, and some individuals, such as the pitcher, have a great deal of control over the pattern exhibited by his/her team. This is sometimes referred to as centralized control (Resnick, 1996).

Because some aspects of the pattern of a process such as a baseball game can be explained as caused by a single or a few individuals, one can also say that these individuals acted with the goal of producing the pattern. For example, a pitcher intentionally pitches a curve ball (a *local goal* for a specific interaction) so that the batter will not hit a home run and thereby his team may win the game (a *global goal*). Thus, a third way to characterize explanations of such intentionality is that the interactions are *goal-oriented—intentionally* undertaken to achieve a *global goal.*

Because the agents in a baseball game often act with an intentional global goal of producing a desired pattern, their interactions therefore *correspond* more-or-less to the overall pattern. For example, if several batters of one team get to first base, then the score of that team (which is part of the baseball game pattern) is likely to get higher and so that team will win the game. Thus, an increase in the number of players reaching the first base corresponds to an increase in the game score. Such correspondence can be further characterized as that interactions of the players correspond *directly* to the game score. Thus, a fourth and fifth way to characterize these explanations is that they refer to agents' interactions that *correspond* to the pattern in a *direct* or *indirect* way. Indirect merely means that some interactions mediate some outcome in the pattern. For example, a hit that gets a player to first base enables the likelihood of scoring another run. Finally and perhaps most importantly, the mechanism causing the pattern of a process such as a baseball game can be characterized as one of *additive* summing. Let's illustrate with one aspect of a baseball game pattern, the score. Suppose the score of a particular game in the first inning is 2, then if three more runners get home in the second inning, then the score of 3 will be added to the score of 2, to sum to 5. That is, the changes in the pattern of such a process are caused by *additive summing*, so that each new pattern is incrementally (the same or) more than the previous pattern. These six characteristic attributes of interlevel causal explanations of a pattern as a function of the agents' interactions are shown in the left column of Table 7.1, and they can be conceived of as constituting one aspect of a Direct Causal Schema.

APPLYING THE SAME DIRECT CAUSAL SCHEMA TO EXPLAIN NONSEQUENTIAL PROCESSES

Everyday processes such as a baseball game, or a skyscraper getting taller as it is being built, might be referred to as "sequential processes" in that the process itself can be decomposed into a sequence of subevents. For example, a baseball game can be decomposed into a sequence of innings. Similarly, many process concepts introduced in middle school science texts are also of this sequential kind, in that they

TABLE 7.1 Six characteristic "attributes" of causal explanations relating the interaction of the agents to the pattern (or changes in the pattern)

	Direct Causal Explanation	**Emergent Causal Explanation**
1	A *single* or a *subgroup* of agents may be responsible for the pattern	*All* the individuals as agents in an entire collection are responsible for the pattern
2	One or more agents have *special* or *differential* status with centralized control	All agents' interactions have *equivalent* status with decentralized control
3	Some interactions are undertaken *intentionally* to produce the pattern	Interactions are undertaken without any awareness (*no intention*) of producing the pattern
4	Agents' interactions *correspond* to the pattern.	Agents' interactions can be *disjoint* from the pattern.
5	Agent's interactions are *(in)directly* related to the pattern.	Agents' interactions are *nondirectly* related to the pattern.
6	The causal mechanism relating the agents' interactions and the pattern is *additive summing* across time.	The causal mechanism relating the agents' interactions and the pattern is *collective summing* within each instance of time.

are either cyclical or stage-like, such as the phases of the moon, stages of human development, phases of cell division (mitosis), photosynthesis, blood circulation, and so on. We assume that students, when they enter middle school, will activate their Direct Causal Schema when they are learning about these sorts of "sequential processes," and will assimilate them and generate explanations in much the same way that they would interpret and explain a baseball game. However, there are many processes in students' environment and in their middle-school texts that are not decomposable into stages, phases, or cycles, and we call these "nonsequential processes," such as experiencing a bottleneck or jam at a doorway when a fire alarm rings. Similarly, in students' middle school texts, many processes such as diffusion, osmosis, floating-and-sinking, electrical current, and natural section, can be characterized as "nonsequential" processes (to be elaborated below). Do students apply their Direct Causal Schema to understand, learn, and interpret these processes? And if so, what happens?

We hypothesize that students do apply their Direct Causal Schema to attempt to understand, learn, and interpret "nonsequential processes." This can be verified by examining students' causal explanations for the patterns of "nonsequential processes." The totality of many such analyses is to portray students as having *misconceptions*, where misconceptions refer to incorrect explanations that are often robust, resistant to instructional refutation, and can be shown to be coherent. We will illustrate with one idealized misconceived explanation of the process of natural selection, in the context of a common example that is popular in middle-school textbooks, the case of the English peppered moth.

Around the middle of the nineteenth century, darker varieties of the peppered moth, which had formerly been very rare, began to spread throughout the industrial regions of middle and northern England. The darkening process followed the appearance of coal smoke over the newly industrialized towns that killed the lichen-encrusted trees and blackened the walls and trees, thus making the lighter peppered-color moths more visible to hungry birds. This evolutionary change can be explained by the process of natural selection. The pattern of this process is the darkening of the moths over generations, and the components of this process are the moths, the birds that ate the moths, the lichen-encrusted trees, and so forth. Thus, the prediction here is that the difficulty of explaining this and other similar processes, in general, is not attributed to the inability of learners to identify the components, nor their inability to visualize the pattern of the darkening pigmentation over time (a common assumption in the literature resulting in many attempts at depicting the pattern level changes using simulations). The difficulty is portrayed below.[1]

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[1] Note that the goal here is not to argue or defend whether this story of the peppered moth is accurate or not. For example, a more recent study showed that there are similar changes in the frequencies of dark and light moth in both Michigan and Great Britain, and yet there was no corresponding change in lichens at the Michigan site (Grant, Owen, & Clark, 1996). The point is to see what aspects of this traditional explanation have been particularly hard for students to understand.

An Idealized Misconceived View

How might a student explain this pattern of the darkening of the moths? In Figure 7.1, the right-most panel (taken and slightly adapted from Bishop & Anderson, 1990) depicts an idealized "misconceived" view of the evolution of the moths, characterizing a composite of students' misconceptions. Beginning with the first generation, there is an initial distribution of melanic pigmentation (some light and some dark moths), arising from the Darwinian principle of "individual variation." We adopt and adapt Ohlsson and Bee's (1992) decomposition of Darwin's theory into five main ideas or principles (shown in quotes here, and elaborated in the next section). Students seem able to correctly understand the principle of "individual variation," thus, accept that there can be six light colored and six dark colored moths, as shown in the figure. Due to environmental conditions, some moths will get eaten and others will survive. The environmental conditions refer to the fact that the tree trunks were getting sootier so that the light colored moths are more likely to be seen by birds and thus eaten. In short, more of the fit ones will survive, due to the principle of the "survival of the fit enough" ("Fit" here means that the darker moths' coloration is more camouflaged by the tree trunk colors so they are less likely to be

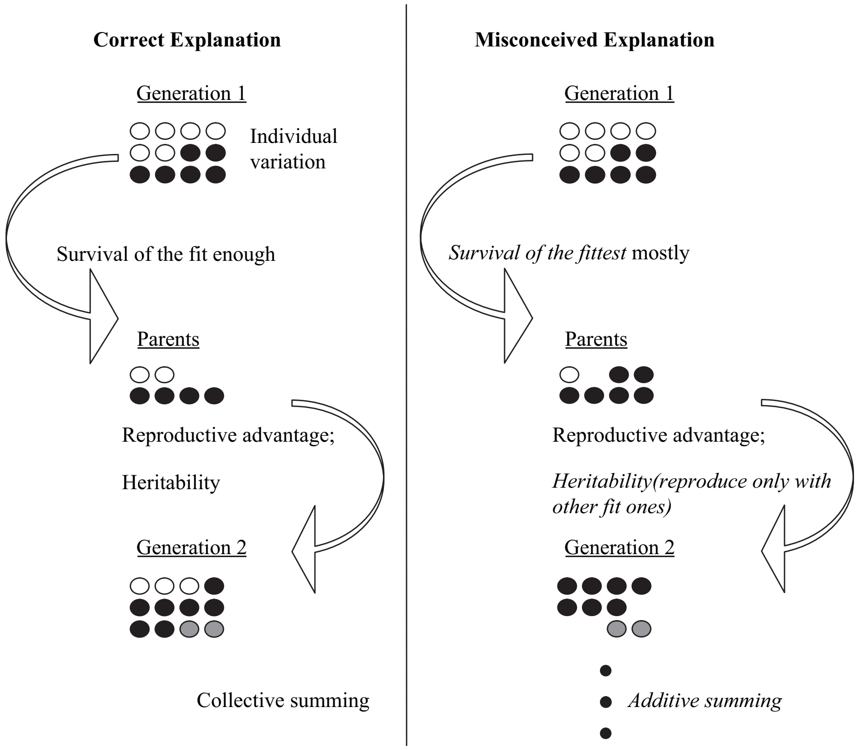

FIGURE 7.1 *The correct explanation (left panel) and a misconceived explanation of moths getting darker (adapted from Bishop & Anderson, 1990). The italics indicate misconceptions.*

seen or eaten by birds). While environmental conditions would lead to a "survival of the fit enough," students misinterpret that principle by wrongly assuming that *all (or perhaps almost all) of the fittest (the dark moths) survive* and all of the light ones die in that generation. In other words, they think of "fitness" in an absolute sense rather than a relative sense, relative to a specific interaction or environment. (In our idealized depiction, we have allowed one light moth to survive. Also, incorrect understanding of a principle is depicted as italicized in Figure 7.1.) They then correctly understand that the surviving moths obviously have "reproductive advantage," in that the ones that survive are able to reproduce. However, students wrongly assume that *the darker moths reproduce only with the other dark moths*, giving birth only to dark offspring, due to the principle of "heritability." Here, their misunderstanding is that they restrict the agents' interactions to other similar ones (dark with dark) and exclude the possibility that a light moth can either reproduce with another light moth, or a light with a dark. This is because they treat and categorize agents (moths) into *subgroups*, rather than treating each moth as an independent *agent* within the population. Thus, it seems that students' failure to understand "heritability" does not lie in lacking knowledge of genetics, but rather, stems from students restricting the moths' interactions to within subgroups, failing to allow for random interactions among all the moths. Finally, students think that the accumulation of changes from one generation to the next is a progression of simple *additive summing*; that is, the number of dark moths from generation 1 to generation 2 either stays constant or increases (but never decreases), since the fit ones always survive and reproduce and the unfit ones die.

In order to suggest that such an idealized misconceived explanation is generated from a Direct Causal Schema, we would have to show that it has the characteristic attributes of a Direct Causal Schema, as listed in Table 7.1 (left column). Because not all misconceived explanations reflect all the attributes of a Direct Causal Schema, we will point out a couple that are embedded in the above idealized explanation. First, in assuming that all of the dark moths survive, students are exhibiting the attribute of *subgroups* (Attribute 1, Table 7.1, left column), in that a subgroup of moths (the dark ones) are responsible for causing the pattern of the darkening pigmentation, and reproductive interactions are restricted to within *subgroups*. Second, they exhibit the attribute of *additive summing* (Attribute 6, Table 7.1), in that they assume that the number of dark moths in each generation is greater or equal to a previous generation; thus they assume that changes over the generations are incremental, arising from an additive summing mechanism. Other misconceived explanations (not shown in our figure, see Evans et al., 2010; or Ferrari & Chi, 1998) may reflect other attributes, such as *intentionality* (Attribute 3, Table 7.1). For example, students often say that the moths want to get darker so that they are not visible to the birds.

The "Attributes" of a Correct Emergent Explanation

A correct explanation for the moth is as follows, and shown in the left panel of Figure 7.1 (adapted from Bishop & Anderson, 1990). The left panel shows the initial population of moths: as before, assume there are six light colored ones and six dark ones. Due to the environmental conditions, more of the fit ones are likely to survive. Thus, only 2 of the light but 4 of the dark ones are depicted as surviving into adulthood. Obviously only the surviving ones get opportunities to reproduce ("reproductive advantage"). In mating after the first round of moths have been eaten, the light ones can reproduce with other light ones, or with other dark ones to give birth to light, medium-dark, or dark offspring (due to "heritability of traits"), or the dark ones can reproduce with each other giving birth to predominantly dark offspring. Since there are by now more dark moths than light ones, there is a greater chance that the dark ones will mate with dark ones, and the light ones will mate with dark ones, creating a new generation of moths that are either dark (let us ignore medium-dark for simplicity) or, occasionally, light. Thus, by the second generation, the proportion of dark moths has increased. Over several generations, the population of moths will get darker and darker. Notice that the pattern of moths becoming darker over time arises from the changes in the proportion of the dark moths as a function of the entire population (or collection), and not the number of dark moths. In fact, the number of dark moths (six originally) can decrease in the first generation (to four) after the fittest ones survive. We will refer to this kind of correct causal explanation for the darkening pattern of the moths as an *emergent* one. As illustrated, such an *emergent* causal explanation can also be analyzed and translated into qualitative characteristics in the same way as we did for naive explanations of everyday processes. Such a procedure allowed us to derive a set of six interlevel "attributes" as depicted in the right panel of Table 7.1. It turns out that these attributes characterizing correct explanations of "nonsequential processes" are diametrically opposed to those characterizing a "sequential process." For example, in the correct explanation, the pattern of moths getting darker is caused by *all* the moths interacting with each other and with birds (Attribute 1, Table 7.1, right column). It is not caused by a *subgroup* of dark moths being the fittest and surviving to reproduce, as a naive explanation believes. Moreover, the agents' interactions and the pattern can be *disjointed* rather than *corresponding* (Attribute 4) in that some light moths can mate with other light moths to produce even lighter moths, thus the birth of a lighter moth does *not correspond, or is disjointed* to the pattern of darkening pigmentation. In addition, the changes over generations are *not additive*, in that it is not strictly the *number* of dark moths that increases from generation to generation to produce the pattern of moths getting darker (see Figure 7.1 right panel), rather it is the *proportion* of dark moths have increased (see Figure 7.1, left panel). Proportion is a value that is computed by considering the entire collection. Thus, the change in proportion over generations is a mechanism of *collective summing* rather than *additive summing*. In sum, we have illustrated three of the six characteristics embedded in a correct explanation of populations of moths getting darker that are diametrically opposite of the characteristics embedded in a naive explanation of the same phenomenon. These are shown in the right panel of Table 7.1.

The last attribute of the causal explanation (Attribute 6 in Table 7.1) is perhaps the most important one, and will be referred to as the *explanatory mechanism*. It essentially explains *how* the interactions at the agent level cause the pattern to be observed. The other five attributes in Table 7.1 (Attributes 1–5) can be described as *characterizing* the relationships between the agents and the pattern, rather than *explaining* the actual mechanism. That is, these five attributes characterize the nature of either a naive or a correct explanation. These five attributes were proposed in the first rendition of this theory in Chi's earlier work (2005). We expand on our prior theory by adding this critical sixth attribute. Its importance will become more evident below.

HOW ARE THE DARWINIAN PRINCIPLES MISUNDERSTOOD?

Students' misunderstanding of processes such as natural selection is often attributed to their failure to understand the Darwinian principles (Ohlsson & Bee, 1992). When studying natural selection, Darwin's theory is often decomposed into five main ideas (or principles): intraspecies or random variation, genetic determination or heritability, differential survival rate, differential rate of reproduction or reproductive advantage, and accumulation of effects across generations or cumulative changes (Chan, Burtis & Bereiter, 1997; Coleman, Brown & Rivkin, 1997; Ohlsson & Bee, 1992). The description of students' misunderstanding of three of the Darwinian principles (*differential survival*, *reproductive advantage*, *accumulation of changes*, italicized in Figure 7.1) can be taken at face value, indicating merely that students have misunderstood them. However, the claim in this paper is that their misunderstanding of these three principles is coherent in that they all fit within a direct causal explanation. Aside from students' misconceived notion that the accumulation of changes is an additive effect (Table 7.1, Attribute 6), we have pointed out in the preceding section how they also misinterpret the two other Darwinian principles (*differential survival* and *reproductive advantage*) in a way that is compatible with a Direct Causal Schema. That is, they interpret differential survival and reproductive advantage as applied to subgroups (as in teams playing baseball from our earlier example) rather than the entire collection (Table 7.1, Attribute 1), perhaps because what is particularly challenging here is the context of a collection (Chi, 2005) or population in this biological context (Foltz, 1992; Helenurm, 1992). For instance, students assume that a subgroup of strong moths will all survive, and the subgroup of unfit ones will all die. Students do not conceive of a light colored moth not being seen and eaten by a bird, thereby allowing a light colored one to survive. Similarly, students misinterpret the principle of reproductive advantage by treating it as occurring within the context of subgroups as well, rather than within a collection. That is, they believe that the subgroup of fit ones only reproduce with other fit ones (e.g., the dark moths reproduce only with other dark moths), rather than allowing the interaction to occur randomly within the entire population, even though there is a statistical bias toward reproducing with other darker

TABLE 7.2 Six characteristic "features" for differentiating the interactions of the agents of a sequential versus a nonsequential process

	Interactions of a Sequential Process	**Interactions of an Nonsequential Process**
1	Distinct or different	Uniform or similar
2	Restricted or fixed	Unrestricted or random
3	Sequential or occurring over time	Simultaneous or co-occurring
4	Contingent or dependent	Independent or unconditional
5	Terminating or bounded	Ongoing or continuous
6	Serve the purpose of achieving a both a local goal and a global goal	Serve the purpose of achieving a local goal only

moths (see Table 7.2, Feature 2, to be explained below). In this misconceived view, evolutionary changes would occur far more quickly than with the correct view.

In sum, we propose that Darwinian principles are difficult to understand not in an absolute sense, but in the context of how they are interpreted. By an absolute sense, we mean understanding what the principles say when they refer to a single interaction. For example, the idea of "survival of the fit enough" is not difficult to understand in the context of a single interaction, that the stronger one will survive. What is difficult is to understand "survival of the fit enough" in a relative sense, that across all interactions, the relatively fitter one will survive. For three of the principles depicted in the moth example in Figure 7.1, *differential survival*, *reproductive advantage*, and *accumulation of changes*, misunderstanding resides in the context of how these principles are interpreted, in terms of subgroups rather than the entire population. For two other principles, *individual variation* and *heritability*, misunderstanding is not captured in this idealized misconceived view. This suggests that perhaps understanding of the Darwinian principles per se is not the problem: the problem is the context of subgroups versus the entire population.

How Can Students Avoid Mis-activation?

Our theory hypothesizes that middle school students apply a Direct Causal Schema to explain all processes. However, even for processes encountered in middle school texts, some of them (which we have referred to as "nonsequential" processes) are not explained by an additive summing mechanism, and instead, must be explained by a kind of collective summing mechanism. The collective summing mechanism of a "nonsequential" process embodies interlevel characteristics as those shown in Table 7.1. Explaining a "nonsequential process" using attributes embodied in a Direct Causal Schema will result in robust misconceptions. Doing so also explains why these misconceptions are biased in one direction, in that students tend to misinterpret a "nonsequential" kind of process as a "sequential" kind, but not the converse. Would it be sufficient to instruct students about the attributes of a correct explanation as identified in Table 7.1 (right column)? Will students be able to then give correct causal explanations for the patterns of processes? No, because there remains another huge challenge of figuring out how to help students discriminate a "sequential" from a "nonsequential" kind of process. The reason the discrimination is so tricky is because the patterns of both kinds of processes look similar, as we pointed out earlier. For example, the formation of a V-pattern by Canadian geese looks almost identical to the formation of a V-pattern by pilots in an air show; the sensation of water flowing feels the same as heat flowing in water; the perception of a light bulb lighting after one turns on the switch looks the same as water coming out of the hose after one turns on the spigot. And yet, these contrasting processes require two different kinds of explanations; whereas students tend to explain them in the same way (Slotta, Joram & Chi, 1995). In short, the perceptual (or imaginable) patterns of "sequential" and "nonsequential processes" look similar, so that students cannot know *when* an emergent causal explanation is the correct one to give, since they cannot discriminate a "nonsequential" from a "sequential" process. In contrast, in our earlier example of learning to identify a whale, there were explicit features (such as a blow-hole) that could easily be pointed to and made salient, which could discriminate a mammal from a fish.

CAPTURING THE CHARACTERISTIC "FEATURES" OF EMERGENT PROCESSES

In order to help students discriminate "sequential" from "nonsequential processes," we propose that the nature of the interactions at the agent level can be used to discriminate them. From similar analyses of various "sequential" and "nonsequential" processes, we derived two diametrically opposite sets of "features" that distinguish agents interacting in a "sequential" kind of process from interactions in a "nonsequential" kind, as shown in Table 7.2. Using a baseball game again as an example of a "sequential" process, the interactions of the components have the features of *distinct*, *restricted*, *sequential*, *contingent*, *terminating*, and directed toward a *global goal*. To elaborate, the players' interactions are *distinct* or *different*, in that they are not all doing the same behavior: the pitcher pitches to the batter, whereas the catcher catches the ball. Thus, the catcher interacts with the pitcher in a different way than the batter, who swings at the ball thrown by the pitcher. By *restricted*, we mean that the components or players are somewhat fixed in terms of with whom they can interact. For example, the pitcher throws the ball primarily at the batter and sometimes the ball is caught by the catcher; the pitcher does not interact with the players of the other team waiting on the side line. Thus, it is not the case that the pitcher is equally likely to interact with everyone. *Sequential* means that the interactions among the players take place sequentially; for example, the pitcher must pitch first before the batter can run to first base. *Contingent*, closely related to the notion of being sequential, means that some interactions are conditional on the outcomes of other interactions. So for example, the batters of one team cannot come to base until the other team has struck out. *Terminating* means that when the pattern no longer can be observed (the pattern is bounded or has an ending), then the behavior of the components stops. Thus, when the baseball game is over, then the players are no longer playing. Finally, the players' local goals of getting to first base, catching a fly ball, and so forth, are related to winning the game (a *global goal*), so that they engage in their local goals intentionally for the purpose of working toward a global goal.

For "nonsequential" processes on the other hand, a diametrically opposite set of features govern the behavior of the agents, consisting of *uniform*, *unrestricted* (or *random*), *simultaneous*, *independent*, *ongoing*, directed at *local goals* only. *Uniformity* means that the interactions of all the agents are not distinguishable. Using the peppered moth as an example again, this means that the interactions of all the moths with birds or other components in the environment, are essentially indistinguishable. That is, moths and birds are both simply flying around looking for food; their interactions consist of a bird eating or not eating a moth, a moth resting or not resting on a tree trunk, or a moth mating or not mating with another moth, and so forth. There can be multiple number of interactions among the agents, but the interactions of all the components are essentially the same (but not identical). They are not identical in the sense that each interaction is subject to local conditions. For example, a specific bird may either eat or not eat a moth depending on the moth's visibility to the bird; but the interactions remain *uniform* among all bird-moth pairs, in terms of being eaten or not being eaten. *Unrestrictedness* means that any component can interact with any other component, so there is randomness in terms of who interacts with whom. Thus, any bird can eat any moth, and a dark moth can reproduce with any other moth, whether dark or light. *Simultaneous* means that these interactions, let's say of birds eating moths, can co-occur everywhere at the same time. In fact each of these interactions (e.g., each bird-eating-moth incidence) can co-occur *independently* of each other. Thus, a bird in one location eating a moth has no bearing on another bird eating another moth in another location. *Ongoing* means that these interactions will continue to occur even if the pattern has reached an equilibrium state. For example, even if the moths have gotten totally dark in color after several generations, birds will continue to eat moths. Finally, birds eat moths for *local* reasons only, such as when a bird is hungry and when a bird can see a particular moth. From the perspective of moths, likewise, they get eaten or not eaten depending on local conditions, such as whether or not they happen to land on a light colored tree that makes them visible. Moths have no *global goal* of intending to get darker over generations. Thus, the features characterizing the interactions of the agents of a "nonsequential" process are clearly antithetical to the features characterizing the interactions of the agents of a "sequential" process.

If students have been taught the attributes of causal explanations, as shown in Table 7.1, will instructing them to differentiate the features of one set of interactions from another set of interactions allow them to identify a "nonsequential" process and thereby give correct explanations? In other words, assuming that the

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features and attributes as shown in the right panels of Tables 7.1 and 7.2 constitute an Emergent Causal Schema (and correspondingly features and attributes in the left panels of Tables 7.1 and 7.2 constitute a Direct Causal Schema), will teaching students this information allow them to learn the process of natural selection correctly and deeply without misconceptions? We describe our first attempt at doing so and the pitfalls we faced.

Pilot Study

Natural selection is a process that is robustly misconceived by middle school, secondary school, college, and even medical students (Bishop & Anderson, 1990; Brumby, 1984; Greene, 1990; Nehm & Reilly, 2007). Our theory suggests that in order to better understand processes such as natural selection, we need to help students develop an Emergent Causal Schema so that they may use the features to correctly identify a nonsequential process, appropriately activate the Emergent Causal Schema, and apply the knowledge embodied in such a schema to generate a correct causal account of the mechanism that explains the pattern of the process. Accordingly, we developed three instructional lessons, based on the earlier version of the theory (Chi, 2005). The earlier version of this theory differed from the current rendition in that it omitted an explanation of the very important sixth attribute of *collective summing* and the sixth feature of not having a *global goal.* (This sixth attribute and feature were added as a result of this pilot study.) The first lesson is about emergence, the second lesson is about diffusion, and the third lesson is about natural selection. Below, we discuss only the first and the third lessons, and the assessment relevant to natural selection.

LESSONS

The first lesson, called the Process Schema, consisted of text materials addressing the existence of and differences between two different kinds of processes, using a contrasting method. We contrasted two everyday examples: *building a skyscraper* as an everyday example of a "sequential" process, and *fish swimming together in a school* as an example of a "nonsequential" process. This schema lesson discussed the ways the components behave, and the differences in the causal mechanism, citing the 10 (not 12) features and attributes that differentiate the two processes, listed as the first 5 in Tables 7.1 and 7.2. In addition, two hands-on activities were conducted with the participants. The activities used a set of different dolls representing people, and the students were directed to make the dolls interact in ways that either produced a bottleneck of people at a gate (corresponding to a "nonsequential" process) or no bottleneck (corresponding to a "sequential" process). A bottleneck or crowding was created by making the dolls interact (walk and shove) at the same *uniform* pace, doing so *simultaneously*, and so forth (depicting the features in Table 7.2). But if the dolls walked at a *different* speed and pace, taking turns walking toward the door *sequentially*, then no bottleneck was created. Embedded in this schema lesson were many questions to test students' ongoing understanding. Without the questions, the text of this lesson was around five to six pages.

The third lesson was about natural selection. There were two sections to this lesson. The first portion was a textual discussion of natural selection. This text was created by selecting and consolidating relevant sentences from five other texts, in order to make the text coherent and improve the exposition. The entire length of this text was around four pages, and covered topics such as traits, variation and inheritance, adaptation, and evolution. The second part of this lesson consisted of a computer simulation, adapted from Wilensky (2001) that showed an emergent pattern of butterflies whose colors gradually matched the background color of the flowers in their environment. Students were shown this simulation, and questions were posed to the students at different points in the simulation. The experimenter/instructor completely controlled the simulation in the sense of either running it or stopping it in order to ask the embedded questions to assess students' understanding.

The study consisted of four sessions, lasting about 2.5 hours each, which took place on four consecutive days. Nineteen students were recruited from a variety of sites, such as public libraries, during the summer months. The participants ranged in age from 11 to 14. On the first and last days, students individually completed the pretest and posttest assessments, respectively. Each test was comprised of 15 multiple-choice questions, 4 short-answer essay questions, and 1 oral response question. All the questions tested students' understanding of natural selection as covered in the lesson, but the oral response question tested far transfer, in that it posed a hypothetical situation in an interview format.

The second day of the workshop focused on instruction about the Process Schema. Students were instructed in small groups of three to five. The students read the textual materials, and the instructor asked them the predetermined embedded questions.

The third day of the workshop focused on instruction about (diffusion and) natural selection. Each topic was taught separately in one minisession. The structure of the instruction was similar to the session of the previous day. Students read the workbook individually, and then discussed the text as well as the embedded thought questions as a group. However, instead of participating in hands-on activities, students discussed computer simulations presenting multiagent models of (liquid diffusion and) natural selection. During the simulations, students responded to questions about the components and the overall patterns produced by their behavior. These discussions were audiotaped. Posttest was administered in the last session.

ANALYSES AND RESULTS

Overall, there were significant improvements for all three types of questions. We will report results for the multiple-choice portion of the pretest and posttest assessments, along with coding from the oral question, since these questions provide the largest amount of data.

Multiple-Choice Questions

The multiple-choice test consisted of 15 questions. Although there was an overall significant increase from pretest to posttest, in order to understand what aspect of natural selection students did not understand, we divided the 15 questions into five categories: five questions about definitions, three about the Darwinian principles, two about the patterns, two about the agents' interactions, and three about the emergent mechanism or an interlevel attribute. Examples of each category are illustrated in Table 7.3.

TABLE 7.3 Example questions for the five categories of the multiple-choice test

Category	**Examples**
Definitions	The term "population" refers to any group of organisms: (a) that can reproduce together to produce living offspring, (b) that share the same name, (c) that live and reproduce in the same geographic location as each other, or (d) that evolved from the same ancestors.
Darwin Principles	Would an island with curly beaked finches also have other types of finches, such as the pointy ones? (a) There would be just one or two pointy beaked ones only, (b) There would be several pointy ones only, (c) There would be a small number of a variety of other types, (d) There would be a large number of a variety of other types.
Patterns	Once a population of finches with similar sized and shaped beaks has lived on the same island for many years, the size of the population will (a) increase rapidly, (b) remain relatively stable with some fluctuations, (c) dramatically increase and decrease each year, (d) decrease steadily, (e) increase steadily.
Agents' Interaction	Which of the following is true about how different finches can interact such that finches involve? (a) Only finches with similarly shaped beaks can reproduce, (b) Finches with similarly shaped beaks are more likely to reproduce with each other, (c) Any two finches (of the opposite gender) can reproduce with each other regardless of beak shape, (d) Two finches (of the opposite gender) with dissimilar shaped beaks are more likely to reproduce than two finches with similar beaks.
Emergent Mechanism	(No correspondence) If a few finches with especially large beaks were hunted and killed on an island, which do you think is most likely to happen? (a) The finch population will develop smaller beak sizes as a result, (b) The finch population will develop large beak sizes as a result, (c) The average beak size will remain about the same, (d) The finches with larger beaks will breed with other finches with large beaks to regain the large beak population.
	(Collective summing) The traits of a population of finches may change over time as: (a) the traits of each finch within the population change over time, (b) the proportions of finches having different traits within the population changes over time, (c) the successful traits and behaviors learned by finches are passed on to their offspring, (d) mutations occur in order to meet the needs of the finches as the environment changes.

There are several points to note about these questions. First, they were quite difficult to generate in a way to assess different features and attributes. Second, they are difficult to answer even though they are in a multiple-choice format. These first two challenges in part stem from the fact that one of the answer options is an often misconceived explanation that students tend to give, obtained from our analyses of the literature. Finally, the questions are by no means perfect; and can be improved. For example, the questions about the Darwinian Principles did not give students opportunities to reveal misconceptions in terms of misinterpreting the principles in the context of a subgroup, as we discussed earlier.

Figure 7.2 shows the results, and they are extremely telling. Not surprisingly (since students were instructed), there were improvements in the first four categories of questions, about definition, about the agents, about the Darwinian principles stated out-of-context (because the questions were stated out-of-context of subgroups, as described earlier) and the pattern. Improvements for the latter two categories were highly significant, and there was a trend for the first two types of questions. However, there was little improvement in understanding the emergent mechanism (including the interlevel attributes). Not understanding the emergent mechanism per se is not surprising, since we did not specifically teach ideas about collective summing nor about proportion change. However, this category of questions also assessed interlevel "attributes" (Table 7.1), which were difficult to understand because attributes characterize the nature of an explanation, rather than the nature of an interaction (in the case of "features," Table 7.2), which is more concrete. Alternatively, the difficulty of the emergent mechanism questions is that they are precisely the ones that address misconceptions. The persistence of their misconceptions suggest that our instruction needs to be improved and possibly prolonged.

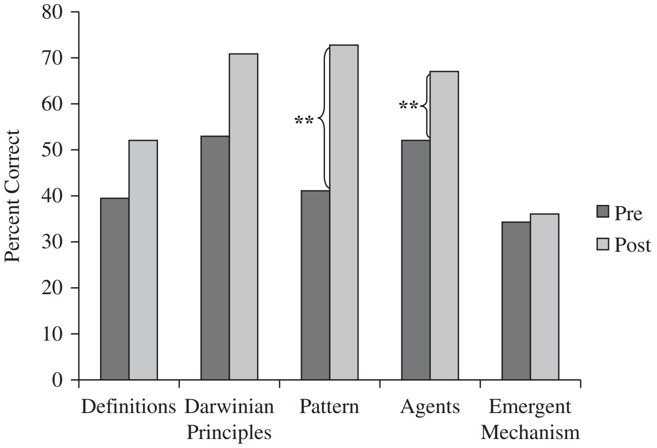

FIGURE 7.2 *Percent correct on multiple choice questions by content. (Two asterisks mean significant at the p < .01 level.)*

One Oral Question

The one oral question, adapted from Ohlsson and Bee (1992), asked an open-ended question about *why some dinosaurs became so gigantic*, and students were encouraged to *invent a scientific explanation* and not to *worry too much about the facts since biologists still disagree among themselves on this point.* The oral response answer was segmented into idea units and coded whether the idea units were correct or incorrect. The correct idea units were further coded to see whether students cited features about the interactions of the agents, described the pattern, or discussed the interlevel attributes relating the agents to the pattern or described the nature of the emergent collective mechanism. Figure 7.3 shows that from pretest to posttest, students' explanations cited significantly more features of the agents' interactions. However, there were nonsignificant changes in students' descriptions of how the pattern changed. This is understandable because there is not much one can describe about the pattern, after the question stated the pattern that dinosaurs became gigantic. What is important is the lack of ideas about either the interlevel relationships between the agents' interactions and the pattern (that were taught in the Process Schema) as well as the actual emergent collective mechanism (that was not taught in the Process Schema).

We also scored the extent to which the incorrect ideas or misconceptions about agents, the pattern, and interlevel relationships or collective mechanisms were reduced from pretest to posttest. Figure 7.4 shows that misconceptions about both the agents and the pattern were significantly reduced. However, there was no significant reduction in the number of misconceptions held, suggesting that understanding the emergent causal mechanism remained difficult.

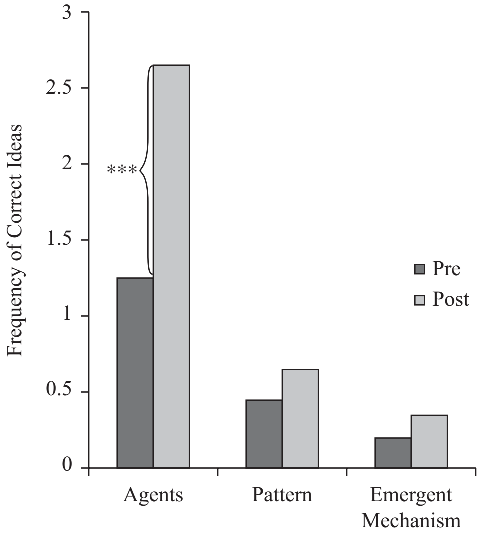

FIGURE 7.3 *Average frequency of correct ideas in students' oral responses. (Three asterisks mean significant at the p < .001 level.)*

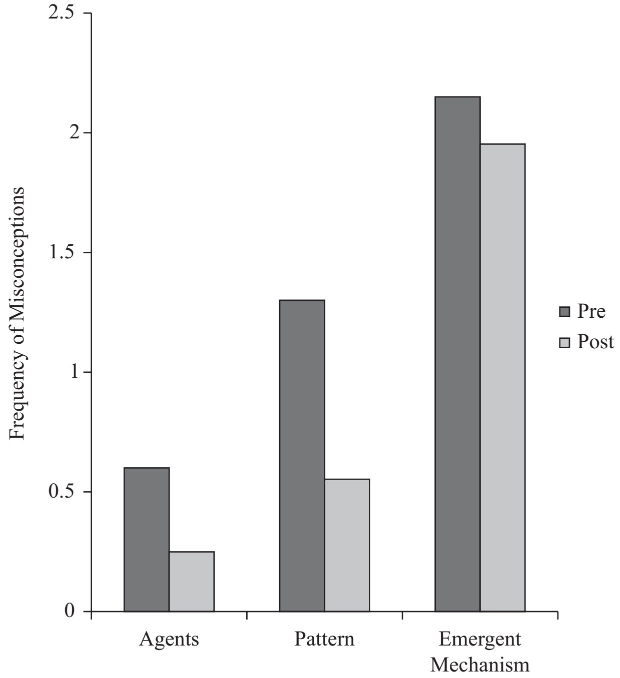

FIGURE 7.4 *Average frequency of misconceptions in students' oral responses. (One asterisk means significant at the p < .05 level.)*

Overall, the patterns of results across three sets of data are very consistent. Students can more easily learn about definitions, Darwinian principles in an absolute out-of-context sense, behavior of the pattern, and interactions of the agents (there were improvements in all these categories, as shown in Figure 7.2, though not all were statistically significant because of our small sample). However, there was little improvement in their understanding of the emergent mechanism or interlevel attributes that are relevant to a correct explanation of the pattern as a function of the collective interactions of the agents. This basic finding is echoed in the results reported in Figures 7.2 and 7.3 for correct ideas, and Figure 7.4 for misconceived ideas. Moreover, these results replicate our prior analyses of a different set of data. In reviewing explanations of speciation, we found no reference to the related concept of "net effect" (see Table 5, attribute 5, in Ferrari & Chi, 1998).

Conclusion

This chapter addresses the question of why students often fail to correctly learn and understand many science concepts and processes, resulting in robust misconceptions. We offer a theoretical account that postulates that most of these robustly misconceived processes are of a nonsequential kind, requiring an Emergent Causal

Schema to understand. However, students lack such an Emergent Schema because their causal explanations of nonsequential processes reflect characteristic features and attributes of a Direct Causal Schema.

One way to remediate this missing schema situation is to help students develop an Emergent Causal Schema, while leaving the Direct Causal Schema intact, as it is needed for interpreting sequential processes. Moreover, an Emergent Causal Schema is ontologically distinct from a Direct Causal Schema, so that we cannot just modify students' Direct Causal Schema to create a variant of it. But how did we overcome the "learning paradox" if the Emergent Schema is a totally and radically new schema? Perhaps not explicitly stated, the ideas presented in this paper suggest that one way to overcome the learning paradox is to present contrasts rather than analogies. By contrasting two kinds of explanations needed for two kinds of processes, we might be able to help students build a new schema. Additionally, the solution to overcoming the misleading cues problem is to focus not on the pattern, but to focus on the nature of the agents' interactions. In short, we have proposed solutions to overcome two challenges specific to this case of learning failures, the challenge of the learning paradox and the challenge of misleading cues.

However, our pilot study revealed new challenges. The pilot study aimed to help students build a new Emergent Causal Schema through lessons we created that describe an emergent schema (using contrasting cases), based on the features and attributes of emergence identified in an earlier version of the theory (Chi, 2005), and embedding instruction about natural selection in the context of such a schema. Our results show that students were able to learn from our instructional materials overall, but their learning was restricted to Darwinian principles and pattern level ideas, with considerable improvements about basic definitions and the agents' interactions. However, there was little improvement in understanding the mechanism of how the interactions of the agents cause the observed pattern. This lack of understanding contributes to the persistence of misconceptions seen in the literature at large, and was perhaps caused by our instruction, which overlooked the need to specifically teach ideas of *collective summing.* Moreover, the simulation we used did not explicitly display how the interactions at the agent level produced the changing pattern. This lesson allowed us to revise our theory to the version described here.

Another lesson learned and predicted from our theory is that learning about misconceived concepts should be differentially assessed, since some ideas, such as about the nature of interactions at the agent level and about the behaviors at the pattern level, are more easily learned and understood than other ideas, such as interlevel relationships and collective summing. Thus, one cannot claim that an instructional intervention has succeeded if only the easy ideas are learned whereas the difficult misconceived ideas remain.

In sum, although our preliminary instructional intervention did not achieve total success, many lessons were learned in terms of what aspects of a "nonsequential process" are particularly difficult to understand. These lessons give us opportunities to revise our theory and hopefully design better instruction to overcome students' deep misunderstanding of emergent processes such as natural selection.

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