Citation: Henderson, J. B., Langbeheim, E., & Chi, M. T. H. (2017). Addressing robust misconceptions through ontological distinction between sequential and emergent processes. In B. Sherin, T. G. Amin, & O. Levrini (Eds.), *Converging perspectives on conceptual change: Mapping an emerging paradigm in the learning sciences* (pp. 26-33). New York, NY: Routledge.

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ADDRESSING ROBUST MISCONCEPTIONS THROUGH THE ONTOLOGICAL DISTINCTION BETWEEN SEQUENTIAL AND EMERGENT PROCESSES

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What makes a misconception robust?

It has been known for several decades now that, while certain misconceptions can be easily overcome through proper instruction, other misconceptions seem to persist even after instruction that specifically targets naïve ideas (Chi, 2005; Confrey, 1990; Reiner, Chi, & Resnick, 1988). What makes these latter misconceptions so *robust*? It has been theorized that at the root of these robust misconceptions is an *ontological miscategorization* of a concept, and hence an *ontological shift* is necessary in order to overcome the robust misconception (Chi, 2005; Chi & Slotta, 1993). Keil (1979) defined an *intuitive ontology* as "one's conception of the basic categories of existence, of what sorts of things there are" (p. 1). More specifically, Keil (1983) describes the concept of *predicability*, which concerns the language *predicates* (i.e., verbs and adjectives) that can be sensibly combined with *terms* (i.e., nouns). According to Keil, two categories are *ontologically distinct* when the predicates of one category cannot be sensibly combined with the terms of another category. Nonetheless, learners have been observed to combine the predicates of one ontological category with the terms of a different, ontologically distinct category. For example, learners have been observed to confuse the assignment of terms to the ontologies of *entities* and *processes* (Chi, Slotta, & De Leeuw, 1994).

When a concept is perceived as having an *entity* ontology, appropriate predicates include attributes such as mass, size, weight, and color. A human being is an entity, for example. In contrast, *processes* are events that occur over time, and hence predicates which pertain to time are appropriate. The biological evolution of human beings is an example of a process. When students encounter a concept they are not familiar with, they conceive of that concept with an ontology, such as an entity or a process. In doing so, they proceed to think of the concept as having the kind of predicates consistent with the perceived ontology. If a concept is perceived with an incorrect ontology, learners will remain committed to that ontological classification. For example, some learners describe an object losing heat as the loss of "hot particles," where the object cools down over time as its total number of "hot particles" decreases. In such a case, trying to convince learners by presenting contradictory or refuting information would be futile for achieving conceptual change. When attempting to refine their understanding, the learners would be looking for ideas that belong to a specific ontological category, and will reject ideas belonging to a different ontological category, for example, that heat is a *process* (Chi, 2013). Hence, according to the *ontological shift* theory of conceptual change (Chi, 1997), what makes misconceptions *robust* is the lack of cognitive access to appropriate ontologies.

However, when studying student explanations of heat transfer, it was discovered that overcoming robust misconceptions is not as straightforward as an ontological shift between entities and processes. When learners describe an object losing heat as the loss of "hot particles," this thinking is not as simple as mistaking a process (i.e., heat transfer) as an entity (i.e., "hot particles") (Slotta, Chi, & Joram, 1995). After all, the explanation described "hot particles" being lost *over time*, and time is characteristic of a *process*. Hence, while the "hot particle" view suggests an entity ontology, the explanation suggests the presence of a schema for processes as well. If what makes misconceptions robust is the lack of familiarity with appropriate ontologies, then what makes the heat transfer misconception robust if the learner possesses schemas for both entities and processes? The answer lies in the fact that learners tend to be much more familiar with one type of process than another. More specifically, there is a tendency for learners to assign predicates to a *sequential* process ontology when they should be conceiving of these attributes with an *emergent* process ontology instead.

Distinguishing sequential and emergent processes

In order to thoroughly distinguish sequential and emergent processes, let us first delineate some important aspects shared by all processes. We can then explain how sequential and emergent processes differ with respect to these aspects. First, processes can be conceived to involve both an *agent* level (i.e., the micro level) and a *pattern* level (i.e., the macro level). Agents can be thought of as the individuated, micro-level elements of a process. For example, in the case of a flock of birds in flight, each bird can be thought of as an individual agent. In contrast, the *pattern level* of a process is the collective, macro-level result of all the individuated activity at the agent level. For a flock of birds, the familiar V-formation in which the birds collectively fly would be a pattern-level observation of the process of bird flight over time. Second, the behavior at the agent level is different from the behavior at the pattern level. While the behavior of a flock of birds appears to take a coordinated V-formation at the pattern level, at the agent level there is no macro-scale coordination, but rather, individual birds are interacting with other birds in their vicinity as they each try to find pockets of air that minimize air resistance.

When we see a flock of birds flying in V-formation, it is tempting to think that the formation is the collective intent of the entire flock. It is tempting to think that the birds are actively communicating with each other as they assume their proper positions toward the ultimate goal of establishing a V-formation, perhaps even paying close attention to the directives of "leader birds" that help orchestrate the collective effort. Such thinking would be a misconception, of course, for two reasons: (1) the process is not coordinated by a central leader, and is therefore *decentralized*; and (2) the process emerges and continues according to a single mechanism, not as a series of events with different mechanisms. Chi, Roscoe, Slotta, Roy, and Chase (2012) claim that the availability of a *Direct Schema* (the term was later replaced with the term *Sequential Schema*—see Chi, 2013), as evidenced by people's ability to comprehend story narratives as well as everyday scripted events, helps explain why it is so tempting for us to interpret the V-formation flocking of birds in a linear, sequential, and goal-driven fashion. A Sequential Schema is what compels us to view the V-formation of the flock as an end goal of the birds, and that a series of interactions between the birds was carried out in accordance with the goal of achieving the V-formation. More specifically, since a Sequential Schema typically involves some sort of triggering event, central characters (e.g., protagonists/antagonists), and a series of actions carried out in accordance with the goals of the central characters, this would explain our temptation to think of the V-formation as the result of a *sequential* process, that is, a series of events that were preplanned and organized by a central command.

In reality, a proper explanation for why a flock of birds appears to fly in V-formation at the pattern level requires an understanding of a process ontology that is NOT sequential. Interactions with a single bird or subgroup of birds does not cause, control with special status, or necessarily correspond to the V-formation observed at the pattern level. There is no intent on the part of birds at the agent level to achieve V-formation at the pattern level, nor does our recognition of the V-formation in its final pattern form require us to recount, one by one, the sub-events leading up to the V-formation. Rather, the interactions of each and every bird in the flock must be considered, both collectively and simultaneously, in order to understand why a V-formation occurs at the pattern level of the flocking process. Such an understanding requires a different and less familiar process ontology—understanding of *emergent* processes.

In addition to living agents such as flocking birds, the sequential/emergent distinction can be applied to processes involving non-living agents as well. For example, if we place a droplet of ink in a container of water, it will diffuse and ink will move to the other end of the vessel. When interpreting the motion of the ink in the water, students often say that the ink particles have a tendency to move to an area of lower concentration because "there are too many particles crowded into one area, therefore they move to an area with more room"

(Odom & Barrow, 1995, p. 52). This type of reasoning represents a misconceived ontological categorization of the diffusion process as sequential, because the explanation aligns the agent-level behavior with the observed macro-level behavior of the pattern. This sequential interpretation also reflects thinking that a subgroup of agents directs the pattern, because the pattern seems to be driven by the ink particles, and not by the water molecules that are also part of the system. As diffusion is in actuality an emergent phenomenon, sequential thinking about the diffusion process is likely to remain robust to change if the less familiar, emergent ontology for processes is not made available.

Clarifications of the ontological shift view

The ontological categorization framework has been used as a guide in several studies (e.g., Jacobson, Kapur, So, & Lee, 2011). However, some aspects of the framework have been subject to critique. In light of that criticism, this update puts forth three clarifications to the ontological shift view.

A. Ontological categorization of process mechanisms is not ambiguous. In many cases, expressions of students' categorization of processes seem to contain emergent features alongside sequential ones. For example, in response to the question "How is it that birds form flocks?" a student wrote, "Cause there is leader in the flock to guide them, also due to survival reasons" (Jacobson et al., 2011, p. 774). The first part of the student response (*there is a leader in the flock to guide them*) suggests that this student thinks one bird has controlling status over an observable pattern, which suggests a *sequential* process categorization of how the pattern is formed. However, the second part of the student response (*due to survival reasons*) might suggest an *emergent* process categorization with respect to the intention of the agents who pursue local goals (i.e., survival) without any intention of creating the V-shape pattern. Such an interpretation might imply a "mixed" or "hybrid" ontological categorization of the process—in one respect the process is categorized as sequential, whereas in another respect the process is categorized as emergent.

Gupta, Hammer, and Redish (2010) claim that such examples suggest that the ways in which people ontologically categorize concepts is often not fixed, but rather, quite flexible. They use several examples of reasoning from informal, classroom, and professional contexts to demonstrate that both experts and novices dynamically move across ontologies as they reason about a given concept. In other words, as opposed to describing conceptual change as a clear ontological shift from one category to another, their examples suggest that experts and novices can utilize multiple ontologies in a flexible manner. More specifically, their examples suggest that perceived ontologies can be sensitive to context, and hence vary from moment to moment. Gupta et al. interpret these findings as inconsistent with the ontological shift view, which they interpret as characterizing a learner to only perceive one ontology at a time.

While we completely agree that experts can shift across ontologies flexibly (Chi, 1997), this is because experts have access to both kinds of ontologies.

Experts may indeed use expressions that suggest an ontological miscategorization, but do so with full awareness that their usage of terms and predicates do not align ontologically (e.g., for instructional purposes). However, whether a process is *emergent* or *sequential*, by our definition, refers to the inter-level causal relation between the micro- and macro-levels. This does not preclude novices from knowing that interactions at the agent level can be intentional and goal-directed. Thus, novices can misrepresent the formation of the V-shaped pattern as caused by a controlling leader bird, and yet at the same time recognize that individual birds may wish to fly in the least exhausting locations for survival reasons. An alternative interpretation for expressions that represent mixed or ambiguous categorizations by novices is that they may represent a transient state in the formation of a sequential process ontology. In this transitional state, the differentiation between emergent and sequential processes is still malleable and the categorical shift has not yet reached its final point.

B. Some emergent processes can be explained entirely at the macroscopic or microscopic level. While the sequential/emergent distinction made above is predicated on how micro (i.e., *agent*) levels relate to macro (i.e., *pattern*) levels of phenomena, for many systems, one can use models of processes that rely on macro-level variables without referring to the constituents at the micro-agent level. Such explanations can be categorized as sequential when the focus is exclusively on macro-scale properties. For example, diffusion can be described using Fick's laws as a consequence of a macro-level *concentration gradient* in the system (Fick, 1855). Such an explanation is legitimate despite the micro-level interactions between particles not being mentioned at all. In this case, as in many others (e.g., heat conduction, electric current, and transitions between different phases of matter), an entirely macro-level representation or an entirely micro-level explanation can provide a legitimate description of the process mechanism as sequential. This is because the only aspect of a process that is emergent is the inter-level mechanism of how the macro-level arises from the micro-level interactions. Hence, if a learner focuses exclusively on either the macroscopic or microscopic level of a phenomenon, the notion of whether an inter-level mechanism is sequential or emergent would be moot, as inter-level thinking requires consideration of *both* the pattern and agent levels.

C. Building upon students' prior knowledge cannot replace a clear definition of the novel ontological category of emergent processes. Our theory does not frame students' knowledge as rigid or static, nor does it contradict the framework that describes knowledge as a dynamic web of ideas that are based on experiential encounters and intuitions (diSessa, 1993). Rather, it provides tools for educators to analyze student thinking and support their construction of proper reasoning. Indeed, building upon students' prior knowledge can be fruitful for explaining natural processes, but must be done with caution. For example, students may know that in some communal animal species, such as a pack of wolves, the alpha male often leads the pack and hence leads the hunt. Thus, a wolf hunt should be described as a sequential process, since the process is coordinated by a central leader. In this case, if an instructor attempts to build upon students' knowledge of the wolf hunt as analogous to bird migration, it may lead students to conclude that the V-shape formation of the bird flock suggests a "leading alpha bird." This result would be a misconceived sequential process categorization of bird-flocking predicated on intuitive knowledge about wolf-hunting. Hence, the awareness and care that instructors should exercise in deciding when it is appropriate to build upon students' prior knowledge.

This is not to say that our approach should not build upon students' prior knowledge. However, we build upon students' prior knowledge as a contrast to what we intend students to learn. That is, our approach is to help students build knowledge of an *Emergent Schema* by directing students' attention to the contrastingly different characteristics of emergent and the more familiar sequential processes. Our evidence suggests that after exposure to differences in the characteristics of emergent and sequential processes, 8th and 9th grade students seemed to have transferred some knowledge of emergence to facilitate their understanding of a science concept prone to robust misconceptions—diffusion. See Chi et al. (2012) for a review of this evidence.

Discussion

This chapter served as an update to the ontological shift view of conceptual change that pertains to certain *robust* misconceptions. These misconceptions do not stem from a confusion between entity and process ontologies, but rather, are rooted in the ontological categorization of different types of processes that learners may be more or less familiar with. Robust misconceptions are resistant to targeted instruction if a schema with the appropriate ontology is not available to the learner. Pointing to a "narrative-like," *Sequential Schema* that develops from our familiarity with storytelling and everyday scripts, we argue that learners are more apt to intuit a concept with a *sequential ontology* for processes than they are an *emergence ontology* for processes. A sequential ontology is predicated by agents with special status that are goal-driven and carry out a series of intentional steps to achieve that goal at the pattern level. In contrast, an emergence ontology is predicated by all agents being on an equal footing, where the simultaneous consideration of local interactions manifests in a macro-scale pattern that was by no means intentional. We suggest this important sequential/emergent distinction can help overcome notoriously robust misconceptions in the sciences. In addition, we clarified three aspects of the ontological shift view. First, the ontological shift view does not consider student thinking to be an inflexible set of ideas. Second, the ontological shift view accepts that emergent processes can be explained using an entirely macro-level or an entirely micro-level representation. Third, the ontological shift view purports that a proper distinction between categories must be presented to students, and that instructors cannot necessarily rely on analogizing and refining prior student knowledge.

We close by suggesting a few open questions regarding the ontological shift framework. Since developing an emergent ontological categorization for processes is difficult, future research should explore which descriptive characteristics make emergent process ontologies more distinguishable to learners than others. It should also gauge more closely the observed paths of change that students demonstrate as they learn to distinguish between emergent and sequential processes. This will enable us to design better scaffolds for building the bridge that will lead to appropriate categorization and analysis of emergent processes. Finally, descriptive characteristics that we have identified to differentiate emergent from sequential processes do not address the mechanism that shows how the pattern level emerges from the agent level interactions. Students need to understand this mechanism in order to generate causal explanations that are not misconceived.

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