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Processing misconceptions: dynamic systems perspectives on thinking and learning

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The study of complex dynamic systems is central to biology. In this essay, I argue that thinking and learning can also be understood as phenomena that emerge from the continuous interactivity of dynamic systems. I first present and apply core concepts of dynamic systems theories to both biological and cognitive systems. I then use these ideas to explain how a dynamic systems perspective can recast the way we think about misconceptions, a central concept in the field of education research. Rather than model misconceptions as object-like entities that students either have or do not have, misconceptions can be modeled as patterns that emerge from continuous cognitive processes. I end by discussing how adopting a dynamic systems perspective suggests a need for research that uses methods designed to study processes in time and can inspire educators to embrace and value variation and fluctuation in students' thinking and learning.

KEYWORDS

dynamic systems, misconceptions, conceptual change, biology education, knowledge-in-pieces

1. Introduction

Biology is often described as the study of complex, dynamic systems—comprised of many heterogeneous components that interact with one another and environments to produce emergent patterns. The concepts and tools of dynamic systems theory have been applied to a range of biological phenomena, from genomes and cells to populations and ecosystems. Across a range of scales, dynamic systems approaches have been generative, contributing new ways of conceptualizing and studying biological phenomena (Kitano, 2002; Kirschner, 2005; Nicholson and Dupré, 2018). Some scholars have proposed that the study of complex dynamic systems is a central unifying concern of the biological sciences, important enough that training students to think about and study biological systems should be central aim of biology education (Jacobson and Wilensky, 2006; Momsen et al., 2022).

The starting point for this essay is that *thinking and learning* are also biological phenomena that emerge from complex dynamic systems. The brains, bodies, and social interactions that make cognition possible are biological after all. More importantly, considering cognition from a dynamic systems view offers a generative set of metaphors, theoretical constructs, and methodological approaches for studying how students think and learn. To make the case that a dynamic systems perspective can be generative for education researchers, I'll apply it to a core issue in education research: the nature of students' *conceptions and misconceptions*.

The term misconception is most often used to refer to a cognitive entity that underlies and explains students' difficulties generating correct explanations or problem solutions. Misconceptions are commonly described as having the properties of coherence, stability, context-generality (Smith et al., 1994; Hammer, 1996; Scherr, 2007).

Debates about the nature of misconceptions and their value in instructional settings have a long history in education research (Smith et al., 1994; Hammer, 1996; diSessa, 2014), and aspects of the debate have made their way into the biology education research community (Maskiewicz and Lineback, 2013; Crowther and Price, 2014; Leonard et al., 2014). While these debates have been cast in many ways, I'll argue that at their core is a difference in ontology: From a dynamic systems perspective, (mis)conceptions are not *things* that students have. Instead, cognition is a continuous *process*, and conceptions and misconceptions are emergent patterns of activity with varying degrees of stability (Brown, 2013).

Overall, the main purpose of this essay is to present an overview of a dynamic systems view of thinking and learning that I believe will resonate with biology education researchers, particularly those with an interest in systems thinking and modeling. I'll begin with a broad overview of dynamic systems grounded in biological examples. Then, I'll introduce "knowledge-in-pieces" as an example of a theoretical framework grounded in a dynamic systems view of thinking and learning (Smith et al., 1994; diSessa, 2002; Brown, 2013). I'll next address how a dynamic systems perspective contributes a way to reconceptualize misconceptions. Finally, I'll discuss the broader implications of a dynamic systems perspective of thinking and learning for biology education research and instruction.

2. An overview of dynamic systems in biology

Although the concept of "systems" in biology and many other disciplines is widely applied, there is no singular "systems view." In this essay, I'll refer to a dynamic systems (DS) view (Thelen and Smith, 1994, 2007; Brown, 2013; Nicholson and Dupré, 2018) to emphasize the following core ideas:

- Processes, as opposed to objects or structures, are the focus of study.
- Change is continuous, and stability is dynamic.
- Boundaries are open, and system behavior is context sensitive.
- Fluctuation and variability are necessary for adaptive change.
- Macro-level shifts emerge from continuous micro-level activity.

In the sub-sections that follow, I'll illustrate each core idea with examples from dynamic *biological* systems before turning back to cognition in Section 3. I intend for the biological examples to illustrate the core ideas in a context that may be familiar to many readers, while also foreshadowing the implications of applying a DS view to thinking and learning. I chose examples that I thought would provoke productive analogies for those with a background in biology but would still be accessible to a general audience. Each sub-section contributes to the larger point that viewing biological phenomena through a DS lens has been generative for the field of biology as, I'll argue, a DS lens can be productive for the field of biology education.

2.1. Processes, as opposed to objects or structures, are the focus of study

It can seem natural to imagine that biologists study things like genes, cells, organisms, or ecosystems, but as Nicholson and Dupré (2018) argue: "Biology does not study things; it studies processes at various timescales" (p. 9). At the core of a DS view is a shift in ontological perspective from viewing the world as fundamentally comprised of objects to composed of interacting processes.

The ontological perspective we adopt changes what we see, notice, and interpret, and therefore the kinds of questions we think to ask. In biological research, a process ontology reorients how we attend to time, change, and causality. Objects seem to wholly exist in any moment in time; a process, in contrast, is necessarily extended in time (Nicholson and Dupré, 2018, p. 11). A thing *is*, and a process *unfolds*. Change is something that may or may not happen to an object, but a process is defined by change (*ibid.*, p. 12). Because of this, when an object remains the same no explanation is required. A process ontology flips that expectation on its head: Because processes are in constant flux, periods of stability or stasis require explanation (*ibid.*, p. 14). Finally, an object ontology can lead us to identify the existence or actions of things as the cause events. A process ontology directs us to look for interactions, not objects, for explanations of cause. Thus, a shift from an object to process ontology changes the focus of study from identifying system components and structures to examining how and why systems change or stay the same over time (Thelen and Smith, 1994; Rogers and McClelland, 2003; Nicholson and Dupré, 2018).

Consider for example how modern approaches to genetics and genomics as the study of dynamic networks compare with classical gene-centric approaches (Burian and Kampourakis, 1991; Dupré, 2004; Kirschner, 2005). If "one gene" codes for "one enzyme," it makes sense that the focus of research efforts would be to identify the "genes for" various traits. We now understand the limitations of this view. First, there is no clear or consistent way to bound or identify something that could be called a gene. Sequence information can be read forwards or backwards, can be spliced together in different arrangements, and can contain multiple start and stop points. Rather than discrete genes, what exists is raw genetic material that can participate in various processes. Second, genetic material has no independent meaning or function. Genetic processes always play out in environmental contexts, and it is only through interactive processes that genetic material can contribute to emergent patterns. Third, genetic products often contribute to multiple functions (pleiotropy) and can function differently in interaction with other gene products (epistasis). Given this complexity, a single gene no longer holds the same causal status it once had (Burian and Kampourakis, 1991; Kirschner, 2005; Keller, 2013).

Researchers might still attempt to name and characterize genes, but they now do so with the understanding that a gene is not the kind thing we once thought it to be—by itself it cannot tell us all that we want to know. Thus, rather than hunting for the presence or absence of genetic variants, it has become important to examine the variety of ways in which genetic material can function in the processes of genetic regulation, coordination, and feedback over time and in response to changing conditions.

2.2. Change is continuous and stability is dynamic

Biological processes are defined by continuous activity—only in death or extinction are they static. Still, biologists are often interested in time periods over which biological entities like cells, organisms, or populations can appear stable even as they continue to change. From a DS perspective this stability is dynamic. A common metaphor that makes the idea of dynamic stability intuitive is to imagine a mountain stream that is continuously moving as water molecules interact amongst themselves and with features of the stream bed (Thelen and Smith, 2007; Nicholson and Dupré, 2018). Such interactions sometimes create stable patterns, as when water rushing past a cluster of rocks forms a whirling eddy. The eddy has a kind of stable structure over time, but that structure is generated by the continuous movement of water—it is dynamic even in its stability.

A second type of metaphor, that of a potential energy landscape, is useful for thinking about different degrees of stability and transitions among different stable states. In these metaphors, the landscape represents an abstract multi-dimensional state space that describes the possible configurations a system can occupy. Depressions, or wells, in the landscape are the simplest way to represent areas of relative stability, or "attractors." Attractors are regions of lower potential energy that a metaphorical rolling ball would be likely to settle into. The depth of a well represents the degree to which a stable state will be resistant to perturbation; in a deep well even a large nudge to the ball might be insufficient to allow it to escape. The width of the well, or the "basin of attraction," represents the set of starting conditions that will lead to the same end state over time.

While the bottom of the well metaphor can make stability seem like a single point in space, in biological systems the ball is never at rest, and attractors are rarely so tightly confined as to be describable as points. More often, attractors describe a constrained trajectory through state space. For example, a two-species system of a predator and prey is often described a settling into a cyclical attractor where an increase in predators leads to a decrease in prey and the decrease in prey then causes a decrease in predators. The cycling pattern is stably maintained by interactions between the two species (unless a sufficiently large perturbation shifts the system to a different trajectory). More complex systems can settle into more complex patterns of attraction.[1]

It is relatively easy to see, in the predator-prey example, how a cyclical pattern is emergent from a process rather than a durable structure. It may be less obvious how to think about an organism as a dynamic system, but the same ideas apply: An organism is also a temporary "pattern of stability" that is maintained through continuous processes of matter and energy exchange (Nicholson and Dupré, 2018). DNA, cells, food webs—at any level of biological organization, the concept of *dynamic stability* provides a way to describe persistent patterns without invoking static objects or structures. From this perspective, we no longer really need to think in terms of things—it is "processes all the way down" (Nicholson and Dupré, 2018, p. 13).

Still, it can be convenient shorthand to name the stabilities in object-like terms, particularly when the processes of interest are stable over the time-period of study. Using a process ontology, we can reinterpret mRNA as a stable constellation of atoms that comes together for a short time and then dissolves again. Yet, there is nothing wrong, for example, with recognizing that a mRNA is stable and "thing-like" on the timescale of minutes. A process perspective does not deny that there may be heuristic value in naming "things," but it does caution us not to forget that time goes on, change is continuous, and stability cannot be taken for granted.

2.3. Boundaries are open, and system behavior is context-sensitive

Dynamic systems in biology are open to the environment, blurring the line between what is internal and what is external to a system (Thelen and Smith, 2007). Genes, cells, organisms, species, do not exist independently of their surroundings. Moreover, levels of context are nested. Genetic activity plays out in the context of cellular activity which plays out in the context of organisms that are experiencing environmental contexts. Each level is permeable to the activity above and below.

One implication of the persistent influence of context is that the definition and role of a system can change as surroundings change. For example, whether or a not a microbe can be classified as a "pathogen" can change depending on interactions with both abiotic and biotic features of context (Bapteste and Dupré, 2013). Models of pathogenicity that include context as part of the system of study change the question from "is this microbe a pathogen?" to "under what conditions is this microbe likely to become pathogenic?" (Nicholson and Dupré, 2018, p. 37). Similarly, even seemingly straightforward "disease alleles" like those that lead to sickle cell anemia function differently in the context of malaria where they shift into a protective role. These shifts in meaning and role have led scholars to caution against extending evaluations of system function or value beyond single contexts (Barker, 2017).

Context also influences system formation and change over time. During development, environments influence patterns of gene activation to produce different phenotypes. As ecological communities assemble, environments mediate processes such as dispersal and species establishment, ultimately impacting community composition and structure. Over time, environmental contexts continue to shape system composition, function, and persistence. At the same time, biological systems are not simply passive recipients of environmental pressures. Dynamic systems have their own mechanisms of responding to change.

2.4. Fluctuation and variation allow for adaptive system change

Fluctuation and variation play a central role in the ability of systems to change adaptively. Natural selection cannot proceed without population variation. Over time, as selected variants increase in frequency in populations, variation in selected traits is reduced. This can lead to a paradoxical situation in which a population that is well adapted to a particular set of conditions does not have sufficient variation to adapt to a new change in the environment. Being able to adapt to a very different environment may depend on the ability of a population to replenish lost variation.

Variation and fluctuation are similarly critical for organism-level development (Thelen and Smith, 1994). For example, in human infants, limb movement is highly variable in speed and direction early in the process of learning to reach. Infants arrive at a functional reaching behaviour by gradually refining and controlling this highly

1 For a visual example see: https://en.wikipedia.org/wiki/Lorenz_system#/media/File:Lorenz_Attractor_Brain_Dynamics_Toolbox.gif

variable movement. Interestingly, different infants reach this endpoint via different trajectories, reflecting a range of "speed personalities" (Thelen and Smith, 2007, p. 296). Some infants reach slowly and need to develop more muscle to stiffen their arms to resist gravity. Others reach too fast and need muscle action to control overreaches and sudden accelerations. Eventually, through repeated, selected action, infants reach optimum reaching behaviour. Yet optima, in biological systems, are always temporary. Infants who have mastered reaching lack the fluidity characteristic of adult reaching. They are less able to adapt from one reach to the next. Infant reaching is also more sensitive to local history than adult reaching, which causes infants to reach towards objects that are no longer there (Smith and Thelen, 2003; Thelen and Smith, 2007).

A final example further emphasizes the importance of variation and fluctuation in adaptability. Cell differentiation is commonly described as a process of stabilization. As undifferentiated cells become more specialized, they can be imagined as settling into stable attractor states corresponding to different cell types (Waddington, 1957). However, stem cells resist stable differentiation and retaining the flexibility to develop into many different cell types. Fluctuation among different regions of state space has been proposed as a mechanism that keeps stem cells from settling into any single attractor, thereby maintaining them in a state of instability and flexibility (Furusawa and Kaneko, 2012).

In dynamic systems, variation and fluctuation counteract stabilizing processes, allowing systems to remain flexible and adaptive. For this reason, variation is not something that can be ignored or that needs to be controlled, but rather a feature of systems that is to be expected and studied, particularly for those interested in understanding the mechanisms of system change.

2.5. Macro-level shifts emerge from continuous micro-level activity

Observations of dynamic systems over long periods of time will show variable patterns of change: Some change can look smooth and gradual, and some change can be dramatic and sudden. A sudden switch in system behaviour is called a phase shift. Metaphorically, this can be imagined as the system being pushed out of one attractor and into another. Climate change for example has caused many ecological communities to reach tipping points where community structure and function is dramatically reorganized. As oceans warm, ecosystems previously dominated by coral species can suddenly become overgrown by algae (e.g., Mumby et al., 2007). Such shifts become possible when multiple interacting changes and feedback loops allow new patterns to emerge.

In much the same way, continuous gradual change among interacting components can explain developmental shifts. According to everyday intuitions, infants move through an ordered series of steps from relative immobility, through crawling, and ultimately to walking. The regularity of this pattern can appear as though it is driven by some hard-wired program, yet no such program exists. Work by Thelen and Smith (1994, 2007) explains how transitions in locomotion emerge from continuous activity of various perceptual and motor systems in interaction with environments. Crawling on hands and knees becomes possible when a confluence of factors such as limb strength, motivation, balance, and coordination come together. Exactly when this happens and how long it lasts varies for different infants depending on how and when these different elements come together. For some infants, hands and knees crawling never happens at all: Their activity assembles into alternative transient forms like belly creeping, or scooting. Other infants skip crawling altogether and progress directly to walking. Research on infant crawling shows that as opposed to a hard-wired progression, developmental stages are transient phases that are "soft assembled" under particular conditions (Thelen and Smith, 2007, p. 274).

From a DS perspective, macro-level shifts apparent in organismal development, evolutionary change, or ecological succession emerge from continuous micro-level processes. Rather than discrete steps or stages, macro-level change can be described as "a series of patterns evolving and dissolving over time, and, at any point in time, possessing particular degrees of stability" (Thelen and Smith, 2007, p. 276). This makes understanding the interactions that produce convergent patterns and shifts among stable states a core goal of dynamic systems research.

2.6. Summary

This overview grounded in biological examples is meant to emphasize how a dynamic systems framework can account for variation and change as well as stability and regularity without the need to invoke direct causes or underlying structures. Next, I'll show how these ideas can be applied to cognitive systems.

3. Thinking and learning from a dynamic systems perspective

Dynamic systems views of cognition have been present in scholarship on thinking and learning for decades, but these views have not been dominant (Thelen and Smith, 1994; Özdemir and Clark, 2007; Brown and Hammer, 2008; diSessa, 2014). More commonly, education research is built on information processing models that draw on computational metaphors. In these models, knowledge is treated as "stored," object-like, in long-term memory and "retrieved" during active thought or problem solving. Learning in such models typically entails replacing incorrect conceptions for correct ones as well as a process of building or restructuring mental frameworks or theories (e.g. Carey, 1986).

In contrast, a dynamic systems view of thinking and learning includes the follow set of core ideas:

- Conceptual processes, not conceptual objects, are the focus of study.
- Change is continuous, and conceptual stability is a matter of degree.
- Boundaries of conceptual systems are open, and thinking and learning are context sensitive.
- Variability and fluctuation allow for conceptual flexibility and change.
- Macro-level conceptual shifts emerge from continuous micro-level activity.

To elaborate on these ideas, I will draw heavily from the conceptual tools and vocabulary of the knowledge-in-pieces (KiP) theoretical framework and related resources-based models of cognition (diSessa, 1988, 1993; Smith et al., 1994; Hammer, 1996; diSessa and Sherin, 1998; Hammer et al., 2005; Wittmann, 2006; Clark and Linn, 2013). KiP originated from efforts to model learners' intuitive reasoning in the domain of physics (diSessa, 1988, 1993) and has been broadly applied within science and math education and beyond (e.g., Clark, 2006; Wagner, 2006; Philip, 2011; Izsak, 2014; Barth-Cohen and Wittmann, 2016), though it has been relatively less common in biology education research (but see Southerland et al., 2001; Lira and Gardner, 2020; Bhatia et al., 2022; Gouvea et al., 2023; Slominski et al., 2023).

KiP explicitly aligns itself with a DS view by proposing that knowledge is a system of heterogeneous elements dynamically linked in a "conceptual ecology" (Smith et al., 1994; diSessa, 2002). Thinking emerges from the selected activity of interacting subsets of elements in particular contexts, while learning entails changes in patterns and stabilities of activation over time.

One type of hypothetical knowledge element is what diSessa (1988, 1993) termed a "phenomenological primitive" (p-prim). P-prims are simple, abstract understandings of how the physical world works that are derived from experience. P-prims are often described as "fine-grained" because they capture simple relationships comprised of small numbers of ideas. At the same time, p-prims are relatively abstract and can be widely applied to a range of phenomena. For example, the p-prim *more effort yields more result* is a simple expression of the relationship between cause and effect that can be abstracted from experiences with a range of specific phenomena: running faster, pushing harder, or yelling louder. Building on this work scholars have identified many different classes of cognitive elements of "resources" that can be conceptual, symbolic, epistemological, or even ideological in nature (e.g., Elby and Hammer, 2001; Sherin, 2001; Hammer et al., 2005; Philip, 2011).

More complex conceptions are modeled in the KiP framework as dynamic networks of interacting finer-grained elements. For example, a "coordination class" describes an assemblage of interrelated elements that together can perform a more complex function, like solving a physics problem (diSessa and Sherin, 1998; diSessa, 2002). In a coordination class, conceptual elements are coordinated with one another to capture causal relationships (e.g., the relationships between force, mass, and acceleration) and with perceptual and regulatory elements that regulate which ideas are activated and applied (e.g., in this situation a force is being applied in the horizontal direction). The assemblage is probabilistically linked such that when one encounters a relevant situation much of the network is activated together. Building on KiP, researchers have used concepts such as framing to model the influence of environmental contexts on the dynamics of resource activation (e.g., Hammer et al., 2005). Learners construct dynamic interpretations (framings) of what kinds of explanations are being asked of them and will offer different sets of ideas as these interpretations shift. For example, students may offer ideas related to the function of leaf color when understanding themselves to be explaining *why* leaves change color and offer ideas about internal mechanisms when understanding themselves to be explaining *how* leaves change color (Louca et al., 2004).

At a general level, KiP and more general resource-based accounts, model thinking and learning in terms of the dynamics of elements (p-prims and other fine-grained elements or resources), ensembles (coordination classes or other more complex patterns), and regulatory processes (framing) (Hammer et al., 2005; Sherin et al., 2012; diSessa, 2018; Sherin, 2018). Thinking emerges from the selected activity of interacting subsets of elements in particular contexts and learning entails changes in patterns and stabilities of activation and organization over time. In the next sections I'll build on this overview to illustrate how these kinds of theories embody core principles of a DS view.

3.1. Conceptual processes, not conceptual objects, are the focus of study

While p-prims are described as knowledge "elements," they are not object-like things. P-prims are dynamic entities—more like organisms or species than static bits of stored information. A p-prim only exists as a pattern of activity maintained through repeated use. diSessa (2002, p. 55) referred to p-prims as capturing "tendencies" in intuitive thought that are both derived from and applied to experiences in the world: The more we push objects and see them move, the more we maintain an intuitive sense that force causes movement. Depending on the timescale of study, these tendencies may exhibit stabilities that make it reasonable to treat them as object-like "entities" or "pieces." However, it is important to understand that what is being named is a dynamic entity not a static object.

Like genetic elements, knowledge elements like p-prims are understood to be multi-functional and epistatic, interacting in different networks to generate different patterns of thought. Consider the example of the p-prim *closer means stronger*, which captures the basic intuition that an effect will be stronger closer to a source. This idea can be applied to a range of gradient phenomena like sound, smell, or temperature. *Closer means stronger* can also appear (incorrectly) as part of a coordinated set of ideas to describe the cause of the seasons as due to the shorter distance between sun and Earth in summer as compared to winter (see, e.g., Hammer, 1996; Sherin et al., 2012).

Because a fine-grained element like *closer means stronger* can participate in different networks, it has no independent existence. It is better described as a relational, quasi-independent entity (Brown, 2013). While one aim of research might be to attempt to identify and name fine-grained elements, the presence or absence of such elements alone will have little explanatory power. As in modern genetics, studying cognition under a DS paradigm requires exploring the dynamic functions of elements in various conceptual processes.

3.2. Change in a conceptual ecology is continuous, and stability is a matter of degree

Cognitive activity is continuous, and yet recognizable and persistent patterns of knowing can emerge from this activity. A coordination class, for example, can exhibit relatively high degree of stability. diSessa and Sherin (1998) described this stability as a one hallmark of expertise in physics. For physics experts, ideas of force, mass, and acceleration have a relatively high probability of co-activation. In addition, experts can recognize how this subset of ideas can be applied to a range of phenomena. They can reliably activate a coordination class to "see" how to apply ideas about forces to problems involving ramps, spring, pendula and so on (diSessa and Sherin, 1998). This feature of a coordination class, also referred to as its "span," is analogous to a wide basin of attraction that will end up at the same set of ideas.

This description of stability in expertise explains consistency in reasoning across contexts, but it is not the same as recalling these ideas wholesale from memory. Dynamic stability is a feature of processes not objects. Each time an expert activates ideas linked in a coordination class will be unique. Because the ideas are probabilistically, not structurally linked, it is possible for each pattern of activation to vary slightly while at the same time functioning with relative consistency across uses.

Novice thought can also exhibit patterns of stability. P-prims, for example, are stable in the sense that they may have relatively high probabilities of activation, sometimes across a wide range of situations. However, KiP predicts that more complex patterns of stability will be less common among novices (diSessa, 2002; diSessa et al., 2004). This is because their experiences in a specific domain are likely to be less systematic than what experts have experienced. In the absence of specific, repeated opportunities for coordinated activation, knowledge networks will retain relative instability. At the same time, stability in novice systems is possible, and can be expected when novice ideas have been functionally useful. Still, all stability is dynamic and contextual. It is a core empirical question of DS perspectives to systemically study the degree of stability and the conditions that make it possible (diSessa et al., 2004; Clark et al., 2011; Sherin et al., 2012).

While I have used the terms novice and expert to illustrate ideas about stability, any individual conceptual ecology has the capacity for both. A relative novice in a domain can bring with them a history of thinking that may be relatively stable, and a relative expert can be fluid and unstable, particularly when introduced to a novel problem (Smith et al., 1994). For any individual, different "regions" of a conceptual ecologies might exhibit varying degrees of stability (diSessa, 2002). From a DS perspective the question is when and in what contexts do we tend to see patterns of stability and when do we see patterns of instability?

3.3. Boundaries of conceptual systems are open, and thinking and learning are context sensitive

Thinking and learning always take place in contexts. Context can refer to conditions surrounding conceptual activity at multiple nested scales, from the local activity of linked elements in a conceptual ecology to interactions with physical, social, cultural, or historical surroundings. An increasingly large body of empirical research has demonstrated that different contexts can elicit different patterns of thinking in both individuals and groups (diSessa et al., 2004; Louca et al., 2004; Wagner, 2006; Nehm and Ha, 2011; Sherin et al., 2012; Watkins and Elby, 2013; Chao et al., 2018; Gouvea and Simon, 2018; Goodhew et al., 2021).

One consequence of contextual embeddedness is that the meaning and function of knowledge elements cannot be understood or assessed independent of context. Recall that the p-prim *closer means stronger* can play a potentially productive role in thinking about gradient phenomena, and it can also participate in non-canonical distance-based explanations for the Earth's seasons (Hammer, 1996; Brown and Hammer, 2008). Independent of context, *closer means stronger* is neither correct nor incorrect. For this reason, intuitive ideas are often described as "resources[2]" that have potential to function in many different patterns of emergent thought (Smith et al., 1994; Hammer, 1997; Warren et al., 2001; Hammer and Elby, 2002; Sherin, 2006).

Shifts in context can also shift patterns of stability. Distance-based explanations of the seasons are reliably provided by people across a range of ages from elementary grades to adulthood. That distance-based explanations for the seasons can be given by college graduates has been viewed as evidence of stability of these ideas to instruction (Brown and Hammer, 2008). However, while distance-based explanations are common in initial thinking, they are not resistant to perturbations such as follow-up questions that ask about hemispheric differences in seasonality. When asked to recall that it can be summer in one location on Earth and winter in another, many middle school aged students switched to alternative explanations, including those that involved ideas about the tilt of the Earth on its axis (Sherin et al., 2012). More generally, KiP researchers caution that any claim that a person has a particular "way of thinking" is likely an artifact of observing them in too narrow a range of contexts (diSessa et al., 2004, p. 865). Even relatively common ideas that span childhood to adulthood may not be stable in the face of shifting contexts and framings.

3.4. Variability and fluctuation allow for conceptual flexibility and change

A rich conceptual ecology, like a variable population, offers more ideas to explore and apply to different situations. That diversity supports generativity should make intuitive sense. The more experiences we have in the world, the more ideas we have available to construct new meanings (Rosebery et al., 2010). And yet because a common goal in education is for students to arrive at a specific set of ideas, there is often a rush to prune down diversity to get students to a singular clear and correct target idea (Sikorski and Hammer, 2010). While strong selection for correctness may allow for efficient arrival at the desired endpoint, it will likely trade-off against diversity. If knowledge resources are labeled wrong or unproductive, students may avoid using them, inadvertently cutting off ideas that could play a productive function in another context (Ball, 1993; Hammer, 1997; Warren et al., 2001; Rosebery et al., 2010). From a DS perspective variation both among and within individuals is to be expected and valued.

2 This usage is similar to the way Keller (2013, p. 41) described DNA as "embedded in an immensely complex and entangled system of interacting *resources* that collectively are what give rise to the development of traits" (*emphasis added*).

Similarly, fluctuation (or reversion) in ways of thinking is often described as "inconsistency"; yet from a DS lens, fluctuations may be an indication of system reorganization (Thelen and Smith, 1994). A micro-developmental study by Yan and Fischer (2002) described multiple types of variation evident as a group of adults were learning to use statistical software. First, each individual exhibited fluctuation in their skill level, switching between using simpler and more advanced strategies. Second, each individual's trajectory was unique. And third, those with less experience exhibited more irregular patterns of fluctuation than those with more experience. Yan and Fischer (2002) argue that not only should variation be expected, but it should also be recognized as an indicator of learning. Learning anything new should require periods of exploration of state space before a conceptual system can settle into the more stable patterns that come with experienced competence.

Finally, variation and fluctuation must be maintained to keep expertise fluid and adaptive. Smith et al. (1994) describe, for example, how variable strategies are a hallmark of mathematical expertise. While textbooks typically emphasize one or two canonical strategies for solving fraction problems, experts use a larger set of strategies and use them in context-sensitive ways. In other words, experts do not simply apply knowledge and strategies in routine ways; rather adaptivity is an important feature of expertise (Hatano and Inagaki, 1986). An expert that can quickly and efficiently solve all the physics problems in a textbook does not necessarily have the cognitive flexibility to come up with creative solutions to novel problems. It may be that for experts, like stem cells, it is important to retain the potential for flexibility; being able to visit and revisit different areas of a conceptual landscape (including "wrong" ways of thinking) contributes to ongoing flexibility and creativity.

3.5. Conceptual shifts emerge from continuous micro-level activity

A core idea of DS models of cognition is that there is necessary continuity between novice and expert—one evolves from the other (Clark, 2006). The p-prim, *more effort yields more result* can be considered the ancestor of more expert understandings of force (diSessa, 2002, p. 35). Such ancestral ideas are not replaced; they are modified and co-opted to perform new functions (Clark, 2006; Sherin, 2006). Experts maintain traces of intuitive thought patterns not simply because intuitive thinking is resistant to change, but because these patterns continue to be functionally selected by evolving conceptual systems.

Given the importance of history and context in conceptual evolution, individual conceptual ecologies will follow their own unique trajectories of change (Clark, 2006; Wagner, 2006). At the same time, common experiences can lead to convergence. Shared experiences with physical phenomena or common curricula as well as mutually reinforcing social interactions can all contribute to shared stabilities among individuals. For this reason, it is possible to identify "common" resources that students are likely to activate when making sense of common phenomena (e.g., Sabo et al., 2016; Robertson et al., 2021).

Still, even if population-level regularity among individuals is observed, sequences of conceptual phases, like phases of ambulatory development or ecological succession, are not predetermined. Instead, like an evolutionary lineage, conceptual development should resemble the emergence and dissolution of a unique series of transient forms.

4. Discussion: a DS perspective on the existence and utility of misconceptions

In this section, I'll use DS ideas to address two issues at the core of debates about misconceptions. First, to what extent are the theoretical commitments associated with the term misconception compatible with or in opposition to DS views? And second, to what extent does the idea of misconceptions contribute to deficit interpretations of student thinking?

4.1. Reinterpreting misconceptions from a DS perspective decreases their prevalence

In general, DS views of cognition have been positioned as in theoretical opposition to conventional misconceptions views (Smith et al., 1994; Hammer, 1996; diSessa et al., 2004; diSessa, 2014). A DS perspective locates the root of the incompatibility in ontology. The traditional view of misconceptions describes them in object-like terms as things that students "have." The properties of coherence, stability, and context-generality follow directly from this object ontology. If misconceptions are stored objects, then there is no expectation that they will change from one instance of recall to another.

In contrast, if cognition emerges from complex dynamic systems, then the properties of coherence, stability, and context-generality will only be possible under certain conditions. There must be some ongoing mechanism or interaction that is functioning to allow a pattern maintain stability over time and across contexts. One possible way to reconcile misconceptions with DS perspective is by reconceptualizing them through a process ontology. If cognition is a process, then a misconception (or any conception) is a special case of conceptual activation that exhibits a high degree of stability (resistance to perturbation), coherence (strong co-activation), and context-insensitivity (Brown, 2013).

However, the possibility of theoretical consistency between the two paradigms does not erase the differences in how these different orientations have informed study design, data collection, and data interpretation. Much like the classical genetics approach to finding "genes for," misconceptions-oriented research is and has been focused on finding the "misconceptions for" students' difficulties and investigating how to remove or replace those conceptions. Overall, this work has not systematically investigated whether ideas characterized as misconceptions exhibit empirical evidence of resistance to perturbation or context invariance. When this has been done, misconceptions have often been found to be less stable and more context-sensitive than initially assumed (e.g., diSessa et al., 2004; Clark et al., 2011; Sherin et al., 2012; Gouvea and Simon, 2018).

In sum, rather than imagine misconceptions as *things*, they can be imagined as patterns that emerge from continuous *processes*. This view suggests that the prevalence of misconceptions in student thinking is often over estimated since characterizations of misconceptions rarely test for stability over time and across contexts.

4.2. How object views of misconceptions can reinforce deficit perspectives

The term "misconception" has frequently been associated with deficit perspectives of students' thinking (Smith et al., 1994; Hammer, 1996; Maskiewicz and Lineback, 2013). A "deficit perspective" is the tendency to interpret a learners' behavior in terms of what is wrong or missing. It is an evaluation of the (lack of) value attributed to students' knowledge or ways of thinking. Deficit perspectives are not intrinsic to theories of learning, and it is possible in practice to adopt a deficit or an asset-based perspective independent of one's theoretical commitments. Still, both language and theory can interact with values interpretations making it relatively easier to adopt deficit perspectives, even if unintentionally.

Some have argued that the term itself—*mis*conception—connotes a devaluing of students' ideas and have called on researchers to use less value-laden alternatives such as "preconceptions" or "alternative conceptions" (Maskiewicz and Lineback, 2013). While the term does emphasize the mismatch between students' ideas and canonical targets, changing the terminology alone does not remove the association between misconceptions views and deficit interpretations. Once again at the root of the issue is the ontological commitment to fixedness. If misconceptions are problematic objects, then it makes sense to devalue them and want to eradicate them.

In contrast, from a DS perspective, no conceptions have an existence that can be evaluated independently from contexts of use. An idea judged as unproductive without a complete understanding the diversity of roles it might play in a student's current or future cognitive ecology can do harm to student learning in several ways.

First, from a basic constructivist perspective, students' conceptual ecologies are the resources from which new patterns of thinking can evolve. Many ideas that have been deemed problematic may have alternative functions that are important. Moreover, exactly how ancestral ideas may be adapted and co-opted in the longer term cannot be predicted. For these reasons, both researchers and educators should exercise caution in making value-judgements about students' ideas. For example, in biology education ideas about organisms' "need" to adapt are frequently described as problematic because they can potentially be used to make claims about directed evolution or mutation (e.g., Nehm et al., 2022). However, the idea of organismal "need" has a sensible function in many contexts. Whether viewed at the timescale of moments or evolutionary time, organisms that cannot meet basic needs such as nutrition, temperature regulation, or safety will not do well. Need can also be viewed as a precursor to more complex ideas about ecological niche or differential selection. As part of a complex dynamic system, there is no straightforward way to remove or suppress an idea, just as there is no easy way to remove a gene from a genome or pluck a species from an ecosystem.

Second, communicating to students that their ideas are "the wrong way" to think can contribute to many other undesirable dynamics. Conceptual elements interact with many other types of ideas including epistemological, affective, and identity resources (Warren et al., 2001; Gupta and Elby, 2011; Warren and Rosebery, 2011; Gupta et al., 2018). The impact of contributing to a student's perception that they are "not good at" thinking within a particular domain can impact their sense of belonging and overall desire to continue to do so. It can also communicate that a student's intuitive ideas or life experiences are generally irrelevant to learning in school and should therefore be ignored (Elby, 1999; Warren et al., 2001). Research in physics education has shown that persistent messaging of this type can lead students to compartmentalize their everyday intuitions and formal physics knowledge, creating fragmented conceptual ecologies in which some ideas make sense and others are correct (Yerdelen-Damar and Elby, 2016). Rather than view an idea as correct or incorrect, a DS perspective invites an ecological view of an idea that allows it to be viewed simultaneously from multiple perspectives: perhaps incorrect in its current application, while also sensible in other contexts and potentially a useful starting point upon which to build.

Third, deficit perspectives are not applied equitably (Lee, 2008; Robertson and Elliott, 2017). Classrooms are sites of cultural intersection and power imbalances within and across cultural communities. In the United States, the ideas and meaning-making practices of white Western communities are privileged (Warren and Rosebery, 2011; Bang et al., 2013; Medin et al., 2014). Ideas that fit these cultural expectations are more likely to be judged as productive, and ideas that do not are more likely to be labeled as incorrect misconceptions. For example, ideas about what counts as "alive" in typical biology curricula teach students to use a predefined set of criteria to decide whether or not something can rightly be described as alive. Warren and Rosebery (2011) describe how an African American student who wondered how the sun could fail to count as alive since it "helps other another thing (a flower)" to grow, elicited concern from his teacher. From the perspective of the Western science curriculum, the idea that the sun is alive has been considered a misconception. Yet, as Bang et al. (2013, p. 305) point out, the definition of alive the includes the sun is just as sensible (perhaps more so) than the view that places the sun in the same category as rocking horse. The concept of "alive," like so many other concepts in science, is itself dynamic and context dependent. Conversations about whether and why it makes sense to categorize viruses, organelles, dormant seeds, or the sun as alive are opportunities to both better understand student thinking and to give them opportunities to participate in and interrogate the dynamic practices of science (Duncan et al., 1991; Warren et al., 2001; Bang et al., 2013).

Scholars who have studied how knowledge functions and evolves in different cultural contexts have long argued for the need to attend to and value heterogeneity within and among cultures (Bang et al., 2007; Lee, 2008; Warren and Rosebery, 2011; Bang et al., 2013; Ladson-Billings, 2014). These scholars often describe their work as "ecological" to explicitly counter decontextualized normative judgements of correctness and productivity rooted in White supremacy. "Cultural diversity" according to Lee (2008), "is evidence of the adaptive systems that human beings have developed in societies in order to exist, to replicate ourselves, and to adapt to changing circumstances" (p. 269). Viewing cultural or "everyday" ways of thinking as deficits ignores their adaptive history and underestimates their value.

5. Implications

In this final section, I briefly summarize some implications of viewing thinking and learning in terms of dynamic systems for education research and instruction.

5.1. Implications for biology education research

Research from a dynamic systems perspective aims to understand how patterns of thinking and learning emerge in interaction with environmental contexts and how those patterns evolve over time. While research that explores dynamic patterns in young learners' reasoning about biological phenomena exists (e.g., Hatano and Inagaki, 1994; Opfer and Siegler, 2004), relative to other disciplines, research from a DS perspective is still relatively underexplored in the biology education research community. In recent years, an interest in DS theoretical perspectives has been growing, particularly among researchers studying biology education at the undergraduate level. In this section I will briefly review some of this emerging work, its significance, and possibilities for future work.

One emerging strand of work has begun to model how students activate and coordinate fine-grained resources in specific problem-solving contexts (e.g., Rodriguez and Towns, 2019, 2021; Bhatia et al., 2022). For example, Bhatia et al. (2022) studied students' reasoning about a set of problems related to enzyme-mediated metabolic reactions. One finding from this work is that students' intuitive interpretations of specific symbols (e.g., a dashed line and a negative sign) influenced the ideas they activated. By detailing these interactions, this type of research moves beyond descriptions of students' responses as correct or incorrect to provide explanations in terms of specific features of the local problem-solving context.

Other work has explicitly attended to differences or shifts in context to explore and test models of context-sensitivity in students' reasoning (e.g., Gouvea and Simon, 2018; Lira and Gardner, 2020; Gouvea et al., 2023; Slominski et al., 2023). For example, Slominski et al. (2023) describe how both course context (i.e., physics vs. physiology) and item-level contexts (i.e., water pipes vs. blood vessels) influenced how students reasoned about fluid dynamics. Studies that model thinking in interaction with context reveal that what students notice and think about can change from one context to the next. As we understand more about how contexts influence biological thinking, we can better understand and anticipate ideas students may be likely to activate in specific contexts and learn more about how they are able to coordinate and reconcile ideas as they move between different contexts.

Understanding how students' conceptual ecologies change over time will require research that follows students over time—from moments to months or years (e.g., Clark, 2006; Wagner, 2006). For example, in the context of mathematics learning Wagner's (2006) extended case study of a learner named Maria describes how she built an understanding of the "law of large numbers" over time by gradually extending the activation of different ideas to different contexts (e.g., problems about coin tosses, spinners, or height in human populations). Such work has helped clarify why abstract concepts are not easily "transferred" from one context to the next; Learners need time and experience across multiple contexts to both build and dissolve associations among different ideas. Understanding how students develop integrated understandings of biological concepts over time is a relatively open area for future research.

The above examples all emerge from the traditions of KiP and resource-based models. In much of this work, "context" has been defined relatively narrowly, in terms of features of problems or classrooms. An important line of research has been investigating cultural influences on students reasoning about the biological world (e.g., Bang et al., 2007; Ojalehto et al., 2013, 2015). For example, Bang et al. (2007) found that both children and adults from Native American Menominee communities were more likely to use ecological and relational ideas when reasoning about plants and animals. Menominee children for example were more likely to see humans as "part of" rather than "separate from" nature than children from European American communities. Studies such as these not only disrupt theories about children's thinking as developmentally constrained, but they also point to the value in studying the diversity of ways in which humans across and within cultures reason about the world. The biology education research community will have much to learn from such cross-cultural studies.

The above examples illustrate how a DS perspective on thinking and learning orients researcher attention to diversity, change, and time. To study these features of thinking, researchers must collect data that allows them to observe these features. Often this means collecting video data of interviews or classroom interactions and sampling across contexts, populations, or over time to capture the dynamics of interest (e.g., diSessa and Sherin, 1998; Sherin et al., 2012).

Analyses of such datasets attend to multiple forms of evidence including what students say in words, paraverbal markers like tone and emphasis, gesture including facial expressions and body posture and explicit attention to various features of context and multiple scales (Sherin et al., 2012; Parnafes and Disessa, 2013). Such analyses require interpretation by multiple analysts to examine multiple interpretations. Importantly, the work of analysists is not constrained by what experts might consider normative, but instead seeks to understand how and why patterns of reasoning make sense *in situ*. This stance allows researchers to better understand the value in diverse forms of student thinking, which in turn can inform how educators can productively engage with this thinking.

Ultimately, this research program will never be able to provide results that will be generalizable to all students. Instead, a DS research agenda, much like research in ecology, will build understandings of *possible* dynamics and mechanisms as well as knowledge about when and under what conditions those dynamics are likely to apply (Hammer et al., 2018). Embracing the idea that thinking and learning are dynamic systems phenomena means expecting and valuing variability, fluctuation, and complexity as intrinsic to cognitive systems.

5.2. Implications for biology instruction

Research from a DS perspective has endorsed high-level principles that can guide both instruction and curriculum development. Most centrally that students' intuitive ideas have value and ecological significance (Ball, 1993; Hammer, 1996; Warren et al., 2001; Lee, 2008; Warren and Rosebery, 2011; Clark and Linn, 2013; Rosebery et al., 2016; Sabo et al., 2016). Whereas much instruction is oriented at identifying difficulties and correcting ideas, a DS perspective invites educators to be cautious in assigning general value to any pattern of thinking, particularly when one lacks information about the dynamics of its stability and ecological function across contexts. Novice thinking develops because it is functional and sensible to students. It is also the raw material from which new functions can evolve. Rather than attempt to remove or replace student ideas, educators should adopt a stance of curiosity towards students' ideas that will allow them to understand both their current functions in students' conceptual ecologies as well as to recognize their potential for future learning.

Second, as with many complex systems, change in cognitive systems takes time (diSessa and Sherin, 1998; Yan and Fischer, 2002; Clark, 2006; Wagner, 2006; Parnafes, 2007; Clark and Linn, 2013). Often this slow pace of change is viewed by researchers and educators as a problem. Students are described as "stuck" or resistant to change. Yet viewed from a DS perspective, rapid change is an unrealistic expectation. Conceptual change is an "evolutionary" process, and while this description does not preclude rapid shifts and reorganizations under certain conditions, more typically change will be slow and gradual as patterns of thinking split or merge and as new associations form and dissolve (diSessa and Sherin, 1998; Hammer et al., 2005; Clark, 2006; Wagner, 2006).

Third, a DS perspective can also encourage instructors to rethink what counts as expertise. Expertise is not a single, fixed endpoint but a state space of multiple dynamic stabilities (Hammer and Sikorski, 2015). Not only does a DS perspective value multiple forms of expertise, but it also recognizes that expertise need not exist at the level of individuals. Expertise could be viewed as a property that emerge from collectives (e.g., Sengupta-Irving and Agarwal, 2017). A classroom community could be viewed as productive even if not every student is playing the same role or changing at the same rate.

Building from these principles, DS researchers have proposed curricular and instructional approaches that are intended to promote these evolutionary processes in cognitive systems. Such curricula attempt to intentionally activate students "raw intuitions" by using familiar examples from everyday life (e.g., Warren et al., 2001; Hammer and Elby, 2003; Geraedts and Boersma, 2006; Clark and Linn, 2013). Then, various approaches are used to help students refine their intuitions, for example by presenting phenomena designed to promote new ways of thinking and by explicitly encouraging students to notice and reconcile inconsistencies that emerge (Linn, 2000; Hammer and Elby, 2003; Clark and Linn, 2013). For example, Hammer and Elby (2003) describe a physics curriculum that builds on the common intuition that when a car and a much heavier truck collide, the car will react more. Students often use this intuition to explain that the car experiences more "force." In the physics curriculum this intuition is first validated as sensible as opposed to incorrect. Then students are asked to consider how to refine this intuition through a series of prompts encouraging them to connect an intuitive sense of "more reaction" to acceleration rather than to force. The design of this curriculum not only builds on understandings of likely incoming intuitions, but it also explicitly attends to the negative consequences of asking students to discount their intuitions or reject their own experiences. This example illustrates what it means to refine intuitions as compared to confronting and replacing wrong ideas.

While curricula designed to connect to students' intuitions have been effective in supporting conceptual shifts on average, it is also important to recognize that such interventions will not work for all students in the same ways or induce change at the same rate. There is no guarantee, for example, that all students will see the connections designers intend for them to see as relevant or sensible to them. There will always be variation among individuals and in their trajectories of change (Hammer, 1997; Clark, 2006; Rosebery et al., 2010).

Instructional approaches such as "Responsive Teaching" take this variation as a given and advocate for instructors to learn how to notice and adapt to unexpected variation as it arises (Robertson et al., 2016, 2022;Rosebery et al., 2016; Louie et al., 2021). Returning to the example of the student who questioned the categorization of the sun as not alive, Warren and Rosebery (2011) imagine how an instructor could see the value in this question. A teacher might notice the intellectual generativity of this idea, how it could be used to examine ideas about energy transformation or ecological relationships not fully captured by the textbook definition. Further, a teacher might hold an appreciation for students as capable of not only learning definitions but also of proposing and thinking critically about the definitions presented to them. As Warren and Rosebery (2011) describe, such a teacher might see such challenging a definition as opportunity to explore the nature and limits of scientific definitions and to position students as able to participate in this practice. Enacting responsive teaching practices requires a willingness to deviate from predetermined sequences and to value ideas for reasons that extend beyond normative correctness. Further, such approaches require teachers to notice and resist their own expectations and biases, which tend to position contributions from White Western cultures as normative and expected (Rosebery et al., 2016; Louie et al., 2021).

Finally, a DS view of thinking and learning should inspire humility on the part of educators. While the role of an instructor is no doubt important, instructors are part of larger complex systems. Intervening on those systems, like intervening on any ecosystem, should come with care, curiosity, and continuous monitoring. While current educational structures like large class sizes and uniform standards makes this ideal difficult to attain, it is still useful to take the perspective that the processes of thinking learning have been continuously flowing before students enter a classroom and will continue to flow and change after they leave. The idea of an instructor as someone who can diagnose and repair should be shifted to an understanding of an instructor as just one part of a dynamic, complex system.

6. Conclusion

Studying complex dynamic systems is central to the study of biological systems. In this essay I have argued that this claim can and should be extended to include the study of thinking and learning. Adopting this view has the potential to be generative, inspiring both methodological and theoretical innovation. Biology education researchers who can think in terms of complex dynamic systems are particularly well-positioned to contribute to this program of work.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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