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Exploring Links between Complexity Constructs and Children's Knowledge Formation: Implications for Science Learning

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Abstract

This essay brings together two lines of work—that of children's cognition and that of complexity science. These two lines of work have been linked repeatedly in the past, including in the field of science education. Nevertheless, questions remain about how complexity constructs can be used to support children's learning. This uncertainty is particularly troublesome given the ongoing controversy about how to promote children's understanding of scientifically valid insights. We therefore seek to specify the knowledge–complexity link systematically. Our approach started with a preliminary step—namely, to consider issues of knowledge formation separately from issues of complexity. To this end, we defined central characteristics of knowledge formation (without considerations of complexity), and we defined central characteristics of complex systems (without considerations of cognition). This preliminary step allowed us to systematically explore the degree of alignment between these two lists of characteristics. The outcome of this analysis revealed a close correspondence between knowledge truisms and complexity constructs, though to various degrees. Equipped with this insight, we derive complexity answers to open questions relevant to science learning.

Keywords: cognitive development, science education, conceptual change, complex adaptive systems, thermodynamics, interdisciplinary theory

1. Introduction

We need to move toward a systems view that describes scientific concepts as complex.

– Andrea A. diSessa [1]

It has long been accepted that children's knowledge formation defies straightforward processes of passive attention and associative learning [2, 3]. For example, rather than absorbing information indiscriminately, children will actively seek out some aspects of information, while ignoring others. Children can also imagine alternative realities, even fantasies that lack a grounding in reality [4]. This poses a problem when it comes to the question of how to improve children's knowledge. For example, it

remains unclear how to support the learning of abstract science concepts, especially when children hold incorrect naïve beliefs about the pertinent science phenomenon [5]. In the current paper, we seek to contribute to this conversation by systematically exploring links between knowledge formation and complexity constructs.

In order to offer a relatively unbiased discussion of the complexity of knowledge, we first identified central truisms about knowledge formation that are broadly supported by the literature. We then provided a glossary of complexity constructs that are potentially useful in understanding knowledge formation. Equipped with these two lists, we then evaluated whether facts about knowledge formation are anticipated by complexity constructs. In turn, this cross-tabulation served as a theoretical anchor to derive answers from complexity to open questions on children's science learning.

2. Established insights about knowledge formation

Picture a child trying to balance a beam on a fulcrum. The principle of physics that matters in this task is that of weight distribution in the beam. While children are capable of detecting the beam's weight distribution, they sometimes focus on the beam's visual symmetry instead. The result is that children have trouble balancing beams with asymmetrical weight distribution; they try to balance them at their geometric center instead of their center of mass. This finding illustrates established facts about (1) the nature of knowledge, (2) the process of knowledge acquisition, and (3) the process by which knowledge is changed (see **Table 1** for an overview).

2.1 Nature of knowledge

A child who insists that a beam should balance at the geometric center is said to hold the mistaken belief that objects balance in the middle [6]. The nature of such a belief (or knowledge, more generally) is necessarily elusive, as it cannot be seen directly. For this reason, numerous models of knowledge have been proposed to rectify phenomenological and empirical findings (e.g., [7, 8]). Considered in the aggregate, the models largely agree on two characteristics of knowledge: (i) that knowledge is organized into structures, and (ii) that there are different kinds of knowledge structures. We elaborate on each of these characteristics next.

2.1.1 Truism 1: Knowledge is organized into structures

Rather than existing as encapsulated factoids, knowledge consists of interlined representations of experiences, also referred to as *schemas* or *mental models* [9–11]. Early evidence for such knowledge organization came from children's systematic errors in Piaget's classical conservation tasks [12]. Children spontaneously and consistently honed in on a particular variable to respond, suggesting the presence of mental structures that make one variable more salient than another. Numerous additional examples stem from errors in categorization tasks [13], causal-reasoning tasks [14], and learning tasks [15]. They suggest that knowledge needs to be conceptualized as an ordered set. A child's belief about beam-balancing is an example of such a knowledge structure.

2.1.2 Truism 2: There are different types of knowledge structures

Agreement also exists that there are qualitative differences in knowledge organization. A prominent distinction is between *implicit* and *explicit* knowledge: Only

Nature of Knowledge	
Structure	Knowledge is organized coherently, rather than consisting of incoherent bits.
Diversity	Knowledge differs in various aspects, including implicit versus explicit, superficial versus deep, or narrow versus broad.
Acquisition of Knowledge	
Holistic construal	Knowledge is actively construed (abducted), rather than being a direct reflection of experiences.
Context dependence	The details of knowledge depend on various contextual factors, including the social context, the nature of specific tasks, and the available tools.
Change of Knowledge	
Persistence	Mistaken beliefs often persist, even to the point of affecting perception, despite their obvious shortcomings.
Role of conflict	Presenting children with the shortcomings of their naïve beliefs creates a conflict that can lead to conceptual change.

Table 1.
Central characteristics of knowledge formation.

explicit, not implicit knowledge, can be reported on [16, 17]. Another example is the distinction between *surface knowledge* and *deep knowledge*: Only deep knowledge, not surface knowledge, can be transferred to new situations [18, 19]. And yet another example is the distinction between *preconceptions* and *misconceptions* (e.g., [20]): While both types of knowledge lead to mistaken performance, only misconceptions, not preconceptions, persist [21]. These and other distinctions proved useful in capturing unexpected behavior, including that of balance-beam tasks [22].

2.2 Acquisition of knowledge

The child presented with a balance-beam task will eventually realize the relevance of weight distribution and succeed in balancing off-center beams. That is to say, the child will eventually learn. This process of learning, like knowledge itself, cannot be seen directly [23]. Sure enough, there are numerous open questions and disagreements about how to best describe the process by which knowledge is formed [24]. There are, however, two characteristics of learning that are broadly agreed upon: (i) that knowledge is construed through the child's activity, and (ii) that aspects of the context strongly affect what is being learned. We elaborate on each of these characteristics next.

2.2.1 Truism 3: Knowledge is construed

At first glance, knowledge appears to reflect outside information, as if outside information was transported into the mind directly. There is indeed suggestive evidence in support of such passive learning [25]. On the other hand, however, there is widespread agreement that learning requires an active mind. Piaget coined the term 'constructivism' to capture this idea: The mind, rather than passively soaking up information, must actively build knowledge. As a result of such construal, knowledge structures might come into existence nonlinearly, reflected in the aha-moment of sense-making (see also *abduction*; [26]). DiSessa [1] captured this nonlinearity in the proposed trajectory from a naïve learner to the conceptually competent individual (see **Figure 1** for a schematic illustration of the suggested nonlinearity).

2.2.2 Truism 4: Knowledge formation depends on the context

Evidence suggests that learning is strongly dependent on the context, even when the context appears irrelevant to the specifics of what needs to be learned. Illustrative evidence of such context dependence can again be found with Piaget's conservation tasks: Despite showing robust performance in the classical version of the task, the mere number of times children were asked for a comparative judgment affected their performance (e.g., [27]). Evidence also comes from the balance-beam task: Children managed to balance the beams better with their eyes closed than with their eyes open [6]. Overall, context (e.g., cultural, societal, physical) has the ability to influence how the information ends up being utilized within the system of knowledge [28, 29].

2.3 Change of knowledge

A child presented with the balance-beam task is unlikely to enter the situation without prior knowledge. It might pertain to general ideas about what to expect, or it can pertain to very specific ideas about how to solve a task (e.g., the belief that beams balance at their center). For science learning to take place, incorrect prior knowledge has to be replaced, a process also known as *conceptual change* [30]. Exactly how to promote conceptual change remains a challenge in science education [31]. At the same time, there are two characteristics of conceptual change that are broadly acknowledged: (i) that existing knowledge structures have a strong tendency to persist, and (ii) that the experience of conflict can prompt conceptual change. We elaborate on each of these characteristics next.

2.3.1 Truism 5: Knowledge structures resist change

There is wide-spread agreement that existing knowledge structures can persist despite strategic changes in the learning context. The domain of science learning is packed with examples of such persistence of mistaken beliefs [32]. It appears as though existing knowledge can affect how one perceives the surroundings, even to the point of inventing improbable experiences (e.g., [33]). The example of beam-balancing illustrates this peculiarity: It is as if children's beliefs about beam-balancing impedes their ability to take in conflicting experiences. In fact, Karmiloff-Smith and Inhelder [6] described children who actively ignored the evidence of a beam tipping over when they attempted to balance it in the middle.

2.3.2 Truism 6: Perceived conflict facilitates conceptual change

Conceptual change is possible when a pedagogy is used that highlights the shortcomings of the existing belief [34, 35]. The power of conflict can be traced to the work of Piaget [36], Festinger [37], and Dewey [38]. The argument is that perceived contradictions generate conceptual conflict, which, in turn, serves as a catalyst for deeper forms of cognitive processing [39]. Presumably, children who hold a naïve belief about beam-balancing can experience conflict as they continue to play with the beams, which, in turn, might prompt them to replace their naïve belief.

2.4 Summary of central characteristics of knowledge formation

In the first part of this preliminary section, we sought to systematize the vast literature on knowledge formation in a way that highlights central characteristics of this process. On the question of the nature of knowledge, we honed in on the

Figure 1. Proposed illustration of knowledge at three stages of the learning process (adapted from [1]). Shapes are thought to be exemplars of experiences represented in the mind. They become organized as conceptually competent knowledge develops. Complexity constructs provide further suggestions to consider.

ideas that knowledge is organized (rather than existing as an isolated fixture) and that several distinct types of organization exist (rather than differing merely in content). On the question of learning, we honed in on the ideas that knowledge emerges via the active involvement of the learner (as opposed to being transmitted passively) and that learning is affected by the context, whether relevant or not (rather than be affected merely by what matters most). On the question of conceptual change, we highlighted the persistence of mistaken beliefs and the power of conflict to prompt conceptual change.

3. Glossary of central complexity constructs

There are excellent sources available to introduce complexity science (e.g., [40–44]). The field of complexity science can nevertheless appear unorganized, featuring constructs that are not fully integrated with each other. It is not immediately obvious, for example, how constructs such as attractors, scale-free patterns, or synchrony relate to one another (or differ from each other, for that matter). This hinders progress on how complexity theory could help with knowledge formation. For this reason, we provide a review of selected complexity constructs. We have organized the list by the type of system that best exemplifies the selected constructs: (1) non-living systems, (2) living systems, and (3) thermodynamic systems (see Table 2 for an overview).

3.1 Constructs from the study of non-living systems

There are several non-living systems that have been used as model domains to explore complex systems, including cellular automata [45], oscillators [46], or electricity grids [47]. Common to all of these systems is that their elements interact with each other. The nature of this interaction is fixed, as is the nature of the elements in these systems. Yet, despite this simplicity, non-living systems can behave in complex ways. Constructs that have been explored in these systems include self-organization, chaos, hysteresis, attractors, autocatalysis, self-organized criticality, and scale-free patterns. We describe these constructs next.

3.1.1 Self-organization

Arguably at the heart of complexity science, self-organization is the process by which global patterns form through local interaction of the system's elements

Constructs from Non-Living Systems	Brief Definition	Living Systems	Thermo-dynamics
Self-organization	The emergence of spatiotemporal patterns through the interaction of system elements.	X	X
Chaos	Behavior is highly sensitive to initial conditions because of the amplification of interacting constraints.	X	X
Hysteresis	A nonlinear shift takes place at a moment in time that is affected by the cumulative history of the system.	X	
Attractors	A behavior toward which the system navigates.	X	
Self-organized criticality	A state of the system in which several behavioral options are available.	X	
Self-similarity (e.g., scale-free patterns, pink noise, fractals)	Patterns are composed of elements that look similar or identical to the patterns they make up.	X	
Constructs from Living Systems	Brief Definition	Non-Living Systems	Thermo-dynamics
Affordance	Sense-making of the surrounding depends on the action of the individual.		
Synchrony	System elements mutually constrain each other as they interact in a circular way.	X	
Self-preservation (e.g., autopoiesis, centripetality)	The system carries out processes that contribute to its own self-maintenance.		X
Constructs from Thermodynamic Systems	Brief Definition	Non-Living Systems	Living Systems
Balance/Equilibrium	The system settles on an organization that is most probable given the existing distribution of energy.		
Dissipation pressure	System elements organize themselves into patterns to dissipate the gradient established by energy clusters.		
Autocatakinetics	System elements become increasingly more organized in the service of the dissipation pressure.		X
Teleodynamics	The coming together of mutually constraining processes that perpetuate each other, seemingly bestowing agency to structures.	X	X
Note: While the complexity constructs are listed under only one type of system, they apply to other systems as well (marked by X in the last two columns of the table).			

Table 2.
Overview of selected complexity constructs, separated by type of system that exemplifies them best.

[48]. When ordered structures are caused by self-organization, there is no blueprint or central control. Instead, the observed pattern is an emergent property [49]. The marking of sand dunes is an example of such self-organization. It stems from the “interplay of windborne transport, collision-driven piling up, and slope-shaving avalanches” ([50], p. 1084). Another example is the synchronization of adjacent metronomes that are initially out of sync. Eventually, the metronomes settle on a synchronized rhythm by virtue of sharing the surface they are placed on [51]. In each of these cases, the interaction among individual elements gives rise to overarching patterns that could be reduced neither to the elements nor the outside.

3.1.2 Chaos

In chaotic systems, future behavior is sensitive to the initial conditions [52]. Chaos can be illustrated with the butterfly effect as a metaphor: A butterfly fluttering its wings over a flower in China can, in principle, cause a hurricane in the Caribbean [53]. A simple system that exhibits chaotic behavior is the double pendulum: Small differences in the initial angles of the pendulum arms are amplified several orders of magnitude in the course of just a few seconds [54]. Chaotic behavior is the result of the coming together of various factors that allow a change to become amplified (or dampened) as the change reverberates through the system. The result is unpredictable behavior of the system, despite having fully deterministic links among its individual elements.

3.1.3 Hysteresis

Hysteresis describes a sudden change in behavior that is modulated by the system's history. Relevant here is the direction in which an outside parameter changes (from low to high, or from high to low). A thermostat provides an illustrative example of this phenomenon: Its function is to detect the temperature of the surrounding to control whether the heat should be on or off. Importantly, the change in the system's on-off status is not necessarily the result of an absolute outside temperature. Instead, the thermostat might have a different temperature threshold for switching the heating on than for switching it off [55]. This allows the thermostat to avoid repeatedly switching the heating on and off when the temperature hovers around the set point. The mathematical branch of *catastrophe theory* provides further specifications of the patterns of hysteresis, including how the presence of an additional outside parameter can modulate hysteresis (see also *cusp-catastrophe*; [56]).

3.1.4 Attractors

An attractor is a state to which the system returns after having been perturbed away from it. Attractors come in several forms, the simplest of which is a point attractor. Consider, for example, a damped harmonic oscillator. The behavior of the oscillator depends on its mass, the spring stiffness, and the damping coefficient—all of which are referred to as control parameters. These parameters determine the details of the oscillator's resting states. If the oscillator were to be pushed away from its resting state, it will eventually return to it, thus demonstrating the state as an attractor for the system [57]. Other forms of attractors are periodic attractors (i.e., the cyclical moving through several stable states; *limit cycle*) and strange attractors (i.e., the non-periodic or chaotic movement through several states).

3.1.5 Self-organized criticality

Self-organized criticality combines the ideas of self-organization and attractors, stating that systems maneuver themselves into a specific state, referred to as the *critical state* [58]. In a critical state, small perturbations can lead to large-scale or catastrophic changes in the system (e.g., [59]). Bak and Chen [59] proposed that the systems attracted to a critical state exhibit $1/f$ noise. The spectral density of the system's response to perturbation can be approximated as: $D_f \approx 1/f^\alpha$ (with $0.50 < \alpha < 1.50$). A well-studied example includes earthquakes, both simulated and real ones.

3.1.6 Self-similarity

Self-similarity is present when the elements resemble the very pattern that they make up [60]. The geometric shape known as the Sierpiński triangle is a famous example: Upon zooming in, the parts of the triangle resemble the triangle itself. The relevance of self-similarity lies in the relation among hierarchically nested patterns. In a self-similar pattern, there are no unique 'starter' elements, as each element is itself composed of entire patterns. That is to say, there is no characteristic scale at which the behavior of a system resides, an idea captured in *scale-free patterns* (see also *cumulative advantage*; [61, 62]). Self-similar patterns are relevant in the understanding of *fractals* and *power-law* distributions, also referred to as *pink noise*. Common to these terms is the idea that there is a long-range dependence among the different levels of organization in a system.

3.2 Constructs from the study of living systems

Like non-living systems, living systems consist of interacting elements that give rise to patterns of organization. Obvious examples include systems of individual animals (e.g., a school of fish, a flock of birds, an ant hill, a group of synchronizing fireflies) or of entire species (e.g., ecosystem). There are also systems within an individual animal, like when cells organize into an organ system [63, 64]. Given the interaction among elements, all of the complexity constructs identified for non-living systems apply here as well. For example, the organizations observed in these systems (e.g., nest building, foraging routes, behavior of crowds) stem from processes of self-organization. There is also evidence of hysteresis (e.g., the switch from fight to flight) and the presence of self-similar patterns (e.g., the branching of trees).

There is, however, a crucial difference between living and non-living systems: Rather than being fixed, elements in a living system can change (see also *complex adaptive systems* vs. *complex physical systems*; [41]). In other words, "living" elements can learn, adapt, and evolve, which, in turn, changes the relation they have to each other. In an ecological niche, for example, entirely new elements can appear (e.g., a new individual in a group), yielding new interactions and configurations. For this reason, some complexity constructs pertain only to living systems. We consider the constructs of affordance, synchrony, and self-preservation.

3.2.1 Affordance

An affordance is the opportunity for action that is made possible by the environment. The construct was developed by James Gibson as an explanation to how animals make sense of and navigate their surroundings [65]. An example of an affordance is the optic flow, a vector field of the perceived motion of static objects

that is established through the movement of an animal. The optic flow does not exist entirely in the surrounding, nor is it a process of internal mental symbol manipulation. Instead, it is caused by the relative motion between an agent and the scene. Many insects have visual systems that are specialized for extracting optic flow. For example, a bee flying through a tapering corridor would experience an increase in translational flow as the corridor narrows, unless the bee slows down [66].

3.2.2 Synchrony

Synchrony refers to the coordination that takes place among the elements of a system (see also *circularity*, *interdependence*, *coupling*). While it can be found in non-living systems (e.g., coupled metronomes), it has been studied extensively in living systems, including in the behavior of molecules, plants, animals, neurons, muscles, bodily regulations, and human relations [67, 68]. There is, in fact, an entire subfield of mathematics focused on theories related to synchrony—namely, to capture the degree to which elements affect each other's behavior in interdependent ways (see also *coupling strength*). When a system is tightly coupled, its elements coordinate closely with each other. In contrast, when a system is loosely coupled, its elements have little to no effect on each other.

3.2.3 Self-preservation

Living systems appear to perpetuate their own organization autonomously, what Darwin famously referred to as a “struggle for existence” [69]. There are a number of complexity constructs that can be used to describe this process of self-preservation. The concept of *agency*, for example, captures the tendency to act on one's own behalf, thus contributing to a system's ability to maintain itself [70]. The concept of *autopoiesis* is another example of self-preservation. An example is the process by which the cells of an organism are able to reproduce and maintain themselves via the production of and interaction between individual elements [71]. Some autopoietic systems can even undergo *recursive self-maintenance* in which the agent is able to select from a variety of processes, depending on their environmental circumstances [72]. Yet another construct that captures self-preservation is that of *centripetality*. This refers to a system's capacity to produce and maintain its own complexity by attracting resources into its circular patterns of self-organization [73].

3.3 Constructs from the study of thermodynamic systems

A third set of complexity constructs stems from thermodynamic systems—systems that illustrate the laws of thermodynamics [74–76]. These systems consist of an energy source, a set of elements that are sensitive to the outside energy source, and a mutually constraining coupling among elements. An illustrative example is a pot of water placed on a burner: The heat from the burner constitutes the energy source; the water molecules are the elements (sensitive to the heat); and the push–pull movement among the water molecules captures their coupling strengths. Another example is an ecosystem [77]: The resources available in the surrounding constitute the energy source; the species of the ecosystem are the elements (sensitive to these resources); and the relations among the species (predator–prey; symbiotic) capture their coupling strength. Relevant constructs from these systems are that of balance, gradient dissipation, autocatalinetics, and teleodynamics. We describe these next.

3.3.1 Balance

Thermodynamic systems move toward a state in which forces are balanced (also referred to as *homeostasis* or *equilibrium*). Grounded in fundamental laws of physics, balance exists when there is no longer any net change in forces, influences, and/or reactions. In that sense, thermodynamics offers a traceable endpoint to behavior (a purpose, so to speak), namely, in achieving balance. Outside of physics, balance is also used to indicate steady or stationary conditions in branches such as evolution, economy, and social sciences [78]. An example of balance is captured in the term of *ascendancy*, which is the degree of relative stability in an ecosystem, shown to increase over evolutionary timescales [79–81].

3.3.2 Dissipation pressure

In addition to endowing systems with the purpose of reaching a balance, thermodynamics also identifies the conditions necessary for systems to do so: The push toward balance comes from the presence of clustered energy. This is because the presence of clustered energy, in addition to affecting the system, also sets up a gradient that needs to be dissipated (captured in the second law of thermodynamics; [82]). For example, the mere presence of clustered heat in a cup of tea sets up a gradient to be dissipated (i.e., the heat clustered in the cup will eventually disperse to reach thermal equilibrium). This pressure to dissipate an energy gradient can push the system to create micro-clusters of energy. In boiling water, for example, water molecules organize themselves into vapor pockets that contain some of the heat (see also *morphodynamics*; [83]). Put differently, the pressure to dissipate an energy gradient provides opportunities for the system to organize itself (see also *antifragility*; [84]).

3.3.3 Autocatalinetics

Under some circumstances, systems become increasingly more ordered, seemingly going against the push for dissipation of clustered energy. Animals and plants, for example, appear to pursue the survival of their species, coming up with increasingly more efficient ways to harness and retain resources. These systems are known to be autocatalinetic [85]. **Figure 2**, adapted from Swenson [85], illustrates how the emergence of progressively more organized forms of a system is possible under the law of maximum entropy production. An external energy source (i.e., one that is outside of a local, open system) clusters to create an energy gradient that must be dissipated in order to reach entropic balance in the broader (closed) global system. In moving toward dissipation, a second cluster of energy emerges in the local system, composed of the self-organized behavior of the system's elements. This energy cluster, in turn, defines another energy gradient, hence another push toward dissipation that contributes to the entropic balance of the global system.

3.3.4 Teleodynamics

Teleodynamics is yet another principle that seeks to explain how elements of a system become increasingly more ordered, despite the push toward maximum entropy [83, 86]. The idea is that order is perpetuated when mutually supporting processes come together. A so-called *autocell* (or *autogen*) is a model system that can illustrate this idea. This model is based on two processes, that of autocatalysis (i.e., the mutual facilitation of two or more chemical reactions) and that of containment (i.e., the forming of enclosures from the biproduct of the autocatalytic reactions). The interaction of these two processes (i.e., autocatalysis and containment) allows

Figure 2. Illustration of autocatalytic closure, adapted from Swenson [85]. The solid frame defines the boundary of a global (closed) system. The dashed circle defines the boundary of a local (open) system within the global one. The energy source E_1 defines an energy gradient (ΔE_1) that needs to be dissipated (F_1) to reach entropic balance (ΔS). In moving toward dissipation, a second cluster of energy emerges (E_2), which consists of the self-organized behavior of the system's elements. This second energy cluster, in turn, defines an energy gradient (ΔE_2) and, thus, another push toward dissipation (F_2).

each of them to continue, even as reactants are used up and the enclosures break apart. The outcome is a self-repair and self-replication of sorts (also see *hypercycles*, *autogenesis*, *negentropy ratchet*; [87–89]).

3.4 Summary of central complexity constructs

In the second part of this preliminary section, we sought to review central complexity constructs in a way that facilitates the attempted link between complexity and knowledge formation. In total, we selected over a dozen complexity constructs, some of which apply to all systems (e.g., self-organization, attractors), and some of which apply to some systems exclusively (e.g., agency, hysteresis). For each of these terms, we offered an explanation at the level of phenomenology, bypassing mathematical advances. Emphasis was placed on providing a general sense of the concepts with explanations that were broad enough to subsume several complexity constructs (e.g., synchrony vs. coordination).

4. Cross-tabulation of knowledge and complexity

The link between cognition and complexity is invoked often, as the quote at the top of the paper suggests (see also [90–94]). However, it is not always clear if the ideas are applied consistently, as neither the field of cognition nor the field of complexity is straightforward. Having provided an organization of both areas (Sections 2 and 3 above), we are in the position to address the link systematically. **Table 3** provides an overview of our cross-tabulation.

4.1 Complexity links to the truisms of knowledge formation

4.1.1 Link 1: Complexity in the structural organization of knowledge

There are several complexity constructs that anticipate knowledge being organized. *Self-organization* is one of those constructs—the idea that elements of a

complex system organize themselves. There is indeed evidence of self-organization in cognitive activity. For example, the idea of self-organization has been invoked to address the origins of language (e.g., [70]), to observe the emergence of knowledge (e.g., [95]), to explain the systematic problem-solving behaviors of infants (e.g., [96, 97]), and to apply effective pedagogy [98]. Hence, it is reasonable to assume that knowledge is self-organized.

Another complexity construct that anticipates knowledge organization is *self-similarity*—the idea that an organized pattern repeats itself at various nested levels. Here too there is evidence that self-similarity applies to cognition. It was studied primarily by looking for *scale-free patterns* in cognitive behavior [99]. The signature of scale-free pattern is a *1/f scaling*, also known as *pink noise* (e.g., [100, 101]). Analyses of the variability in reaction time have revealed pink-noise patterns, indicating that the variability in a short time series is similar to that in a longer time series (e.g., [102]). Hence, it is reasonable to assume that knowledge is organized in scale-free patterns.

4.1.2 Link 2: Complexity in the qualitative difference in knowledge structures

There is no obvious complexity construct that capture the distinctions between different types of knowledge. At the same time, the complexity angle constrains the

	Nature of Knowledge		Acquisition of Knowledge		Change of Knowledge	
	Structure	Diversity	Construal	Context	Persistence	Conflict
Constructs from Non-Living Systems						
Self-organization	X		X			
Chaos				X		
Hysteresis				X	X	
Attractors					X	
Self-organized criticality		X		X		
Self-similarity	X					
Constructs from Living Systems						
Affordance			X			
Synchrony			X			
Self-preservation					X	
Constructs from Thermodynamic Systems						
Balance/ Equilibrium					X	X
Dissipation pressure						X
Autocatal kinetics/ Teleodynamics					X	

Note: The columns correspond to the six knowledge truisms described in **Table 1**. The rows correspond to the complexity constructs described in **Table 2**. The X marks the proposed relevance of a complexity construct for a given knowledge truism.

Table 3.
Relevance of complexity constructs to knowledge formation.

ways in which organizations can differ. For example, given that complex systems consist of elements that interact with each other, differences need to be limited to the elements (e.g., number, type) or the way elements interact (e.g., coupling strength). *Graph theory* can specify the number of connections, thus distinguishing between qualitatively different networks (e.g., small-world networks, scale-free networks). And *ascendancy* can capture the coupling strength among elements, thus differentiating systems of various stabilities [80].

Applied to cognition, several complexity measures have been developed to capture coupling strength [103, 104]. These include a child's reasoning during a gear-turning task [105], a child's predictions of the faster sinking object [106], and a child's attempts to balance beams on a fulcrum [107]. Thus, it is reasonable to assume that knowledge structures can differ in the number of mental elements and/or in how the mental elements combine. The organization of preconceptions, for example, might be more restricted than the organization of misconceptions.

4.1.3 Link 3: Complexity in the construal of knowledge

There are several complexity constructs that capture the idea of knowledge construal. *Self-organization* is one of these constructs: It states that the system's organized behavior emerges without a direct linear cause–effect relation. Thus, it rejects the idea that an outside force can specify the exact details of the system's organization. Work on children's stepping behavior has provided early evidence for this conceptualization [108]. More generally, knowledge construal is likely to be self-organized, too.

Affordance is another complexity construct that emphasizes the separation between outside forces and internal organization. This construct rejects the idea altogether that there is objective outside information. Affordances are instead intricately linked to the agent's actions and action capabilities, and thus exist as part of the agent's knowledge structure. In the field of cognition, the concept of affordance can be seen in research of networks that explain decision making, working memory, and mental representations [109–111]. Thus, it is possible that knowledge construal is analogous to the emergence of an affordance.

The construct of *synchrony* hints at a possible mechanism by which a system's organization could be construed. It captures the idea that elements affect each other in a mutually constraining way. This resulting interdependence of elements can amplify the initial coordination to the point that it no longer reflects the outside that gave rise to it (see also *interaction-dominant cognition*; [112, 113]). Synchrony has been used to map out neural connections (see also *connectome*; [114]) and the neural networks that give rise to cognitive performance [115–117]. More generally, there is evidence of synchronization between brain activity and the body/physiology that has been used to capture cognition (e.g., [118, 119]).

4.1.4 Link 4: Complexity in the context dependence of knowledge acquisition

There are several complexity constructs that anticipate context effects (i.e., that seemingly irrelevant changes in context can affect children's learning). Consider, for example, the construct of *self-organized criticality*. This construct describes a system that has several different possible organizations available, which are decided upon by only miniscule changes in the context. Thus, context effects are at the essence of this complexity construct. Indeed, there is evidence that self-organized criticality plays a role in knowledge formation ([113, 120, 121]; see also *metastability*; *multistability*; [122, 123]). Therefore, the context effects seen during learning might be the result of such self-organized criticality.

More generally, the power of seemingly irrelevant aspects of the outside are highlighted by the constructs of *chaos* (i.e., sensitivity to initial conditions) and *hysteresis* (i.e., sensitivity to the history of the system). Here again there is evidence that these concepts are applicable to cognitive processes [124]. Stamovlasis [125], for example, has demonstrated hysteresis in students' science learning, modulated by parameters such as logical thinking ability. Thus, it is possible that context effects seen during learning might be the result of the inherent complexity of knowledge formation.

4.1.5 Link 5: Complexity in the persistence of knowledge structures

There are several complexity constructs that anticipate persistence in the organization of a system's elements. *Hysteresis* is an example of such a construct, namely, because it captures the lingering of a specific organization past outside changes. The construct of *attractors* captures the idea of persistence more generally—that a system's organization can resist perturbation and return to its preferred behavior once the perturbation ends. Applied to children's cognition, the idea of an attractor was used to explain perseverative search behavior [126]. It has also been examined in the study of recurrent neural networks [127, 128]. Thus, it is reasonable to assume that knowledge persistence is the result of an attractor.

The constructs of agency, *autopoiesis*, *autocatakinetics*, and *teleodynamics* have also been linked to human behavior [129, 130] and mental activity (e.g., [83, 85, 130–134]). In fact, Barab et al. [131] have applied the idea of autocatakinetics specifically to children's science learning.

4.1.6 Link 6: Complexity in the role of conflict in conceptual change

There are two complexity constructs that anticipate the power of conflict to change a system's organization: that of *balance* and *dissipation pressure*. Both of these constructs stem from the study of thermodynamic systems. Under this framework, the perceived conflict can be conceptualized as something that changes the balance of forces and, thus, changes the dissipation pressure. These changes, in turn, affect the likelihood that an existing organization can no longer dissipate the pressure, ushering the change in organization.

The concept of balance is not foreign to work on children's cognition [135]. For instance, Piaget's constructivist account of cognitive disequilibrium highlighted the interplay of the counteracting processes of transformation and conservation [136, 137]. Also, Piaget's notion of adaptation is seen as a process of equilibration between processes of assimilation and accommodation [138]. The role of perceived conflict fits well within this line of work. Thus, the complexity angle offers a way of conceptualizing the role of conflict in ways that are consistent with systemic laws.

4.2 Summary of how complexity is linked to knowledge formation

In this section, we sought to explore the extent to which selected knowledge truisms align with complexity constructs. Our analysis showed that this link is indeed present, though to various degrees: Most prevalently, complexity anticipates the organization of elements and the persistence of knowledge. It also anticipates the influence of the outside context and the impact of conflict on conceptual change. Note, however, that complexity constructs differed in how well they covered knowledge truisms. For example, the idea of knowledge construal was covered by several complexity constructs, while the idea of knowledge persistence was covered primarily by thermodynamic constructs. It remains to be seen if this disparity

identifies a shortcoming of the current theorization of complexity or our interpretation of knowledge findings.

5. Implications for science learning

Having provided an alignment between complexity constructs and knowledge formation, we now derive complexity answers to the ongoing questions related to children's science learning. We specifically focus on questions of (1) how to best define knowledge, (2) how to support children's learning, and (3) how to replace children's mistaken beliefs with scientifically valid insights.

5.1 How to best define knowledge and its elements

While it is widely accepted that knowledge is more than a set of isolated factoids, there is uncertainty about how to best conceptualize such interconnected whole. Complexity provides important constraints for the depiction of knowledge. By this conceptualization, knowledge is defined as the coordination among elements, analogous to a set of synchronizing metronomes, a flock of birds, or an ecosystem. That is to say, knowledge is stable only in the continuous interaction among mental elements. Accordingly, **Figure 1** might need to be revised: Whether understanding is naïve or competent, mutually constraining interactions among elements are required in both. Even elements might be synchronized patterns of interacting parts.

There is also uncertainty about how to capture different types of knowledge unequivocally—for example, between novices and experts. In the balance-beam task, for example, it is still debated whether the difference between implicit and explicit knowledge spans four levels [139], seven levels [140], or none at all [141]. Complexity sheds light on the matter by specifying the ways in which structures can differ. Correspondingly, implicit knowledge might consist of few elements that are constrained to a local action. Explicit knowledge, in contrast, might involve elements that span various circumstances and thus couple with each other on the basis of symbolic correspondences that can be verbalized.

5.2 How to support children's learning

There is no agreed-upon understanding of the processes that turn information into knowledge. Complexity science specifies that this process involves the synchronization of experiences into a self-sustaining whole. Furthermore, thermodynamic constructs show that such synchronized aggregations emerge when there is a balance between clustered energy and pressure. Thus, to decide on the ideal pedagogy, one must first identify the 'clustered energy' in the learning context, as well as the nature of 'pressure'. One must then ensure that these two aspects are in some sort of equilibrium to allow for learning.

Applied to the balance-beam task, clustered energy could be conceptualized as information about the beams (visual, haptic). There is also information across trials, for example, that some of the beams balance at their geometric center. The pressure, on the other hand, could be conceptualized as the task that children are asked to complete: to balance individual beams on a fulcrum. The narrower the fulcrum, the more pressure there is on the system to organize its elements. For pedagogy to be effective, therefore, the salience of the beam's weight distribution must be calibrated with the narrowness of the fulcrum upon which the beam should be balanced. This calibration between information and task pressure has to fit the competence of the individual child and adjust flexibly to changing competences.

5.3 How to replace mistaken beliefs with scientifically valid insights

The challenge in science education has been largely attributed to the presence of mistaken beliefs. However, the results are mixed on the recommendation to assess existing beliefs first, prior to administering a science lesson [142–144]. Complexity science can again shed light on the issue. Specifically, lessons derived from thermodynamics provide a cautionary note to the logic of first providing children with an assessment. This is because, in the language of complexity, assessments are equivalent to the pressure on the system to organize itself. This pressure might force children to come up with ordered behavior that resembles a belief. The risk, therefore, is that the assessment pushes the learner to form an ad-hoc belief, rather than assessing the presence of an already existing belief.

The solution lies in combining pressure (the assessment) with support (the information relevant to the solution), rather than offering the assessment on its own. This recommendation is in line with the resubsumption theory [144, 145]. It is also in line with the finding that a child's explicit goal to change mistaken beliefs has a positive effect on learning [146–148]. This is because such explicit buy-in from the learner shifts the nature of the pressure in ways that allows children to actively search for scientifically valid patterns (vs. latch onto the most obvious patterns to coordinate experiences).

Ultimately, the complexity viewpoint implies that the challenge of science learning lies in the nature of science itself, rather than in the presence of mistaken beliefs. This is because the patterns of order relevant to science concepts are often hidden behind more salient but irrelevant science concepts. For example, in the case of balance beams, visual features are likely to have priority over haptic features, making the irrelevant aspect of the beam's shape more readily available than the relevant weight distribution. Therefore, to improve science learning, one would need to invest in ways of making relevant patterns of order more salient than irrelevant ones, paired with gearing children's action toward detecting these relevant patterns.

5.4 Summary of complexity-based answers to open questions

In this section, we sought to address practical implications of a complexity view of learning. On the question of the nature of knowledge, for example, complexity science provides details on how to conceptualize the interaction of mental elements that gives rise to knowledge. And on the question of learning, complexity science can pin down the pedagogy that could help children ignore irrelevant aspects of the context. The complexity angle can even address questions about conceptual change: It undermines the common suggestion of assessing children's naïve beliefs in the absence of instruction; and it highlights strategies that can help children learn about abstract science concepts. While these suggestions are merely hinted at, they can offer an important impetus to science-education research.

6. Conclusion

In line with the volume's goal of deepening the meaning of complexity, we traced the connection between complexity constructs and children's learning. Our specific focus was on children's science education, a topic with remaining open questions despite previous attempts to apply complexity ideas. Our rationale was that neither the field of complexity nor the field of children's learning are streamlined: Both areas feature inconsistencies and gaps [149]. The synthesis we offered was designed to substantiate this link, potentially fostering progress in both fields.

Our approach started with a preliminary step—namely, to consider issues of cognition separately from issues of complexity. To this end, we defined central characteristics of knowledge formation without considerations of complexity; and we defined central characteristics of complex systems without considerations of cognition. This two-pronged preliminary step made it possible to explore the link between complexity and learning in a principled way, rather than trying to prove a-priori assumptions about it. Thus, by cross-tabulating the list of knowledge truisms with the list of complexity constructs, we were able to substantiate the knowledge–complexity link in a relatively objective way.

The cross-tabulation shows that our chosen knowledge truisms were anticipated robustly by complexity constructs. Building on this alignment, we were able to derive answers relevant to science education. For example, the knowledge-complexity alignment specifies that knowledge is a mental synchronization of experiences. Such synchronization can emerge when there is a balance between direct instruction and active learning that is calibrated to highlight relevant patterns of order (vs. irrelevant patterns of order). This calibration can be difficult to establish when relevant patterns are inherently hidden, as is the case in abstract science concepts. In turn, this difficulty can explain the challenge of science education, going against the prevailing assumption that science-education challenges stem from children's misconceptions.

A limitation of this work pertains to taking some shortcuts when generating the two initial lists. For example, we settled on six knowledge truisms, potentially at the expense of important nuances. And we prioritized prominent complexity constructs, potentially at the expense of lesser-known constructs. We also overlooked ongoing controversies, for example on the topic of constructivism, on self-organized criticality, or on how to apply thermodynamics to cognitive processes. For these reasons, our lists are undoubtedly incomplete. Nevertheless, this work offers a starting point from which to develop a complexity-based framework for children's learning.

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