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The theoretical foundations of enaction: Precariousness

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ABSTRACT

Enaction is an increasingly influential approach to cognition that grew out of Maturana and Varela's earlier work on autopoiesis and the biology of cognition. As with any relatively new scientific discipline, the enactive approach would benefit greatly from a careful analysis of its theoretical foundations. Here we initiate such an analysis for one of the core concepts of enaction, precariousness. Specifically, we consider three types of fragility: systemic, processual and thermodynamic. Using a glider in the Game of Life as a toy model, we illustrate each of these fragilities and examine the relationships between them. We also argue that each type of fragility is characterized by which aspects of a system are hardwired into its definition from the outset and which aspects are emergent and hence vulnerable to disintegration without ongoing maintenance.

1. Introduction

In their seminal writings in the 1970s and 1980s, Humberto Maturana and Francisco Varela put forward a wide-ranging conceptual framework for biology founded on the concept of *autopoiesis* (Maturana and Varela 1980; Varela 1979). Over 50 years later, this framework continues to influence thinking in theoretical biology. Their approach draws inspiration from cybernetics and systems theory. It offers a contrast with perspectives that emphasize functional or teleological explanations in terms of information and evolution. Without denying the importance of these and other functional concepts, understanding life in autopoietic terms entails giving an account of what an organism is and how it operates in the here and now without appealing to larger scales and contexts, such as those of developmental or evolutionary history. Sometimes, this contrast is expressed in terms of the difference between operational (mechanistic, systemic, processual) and symbolic (teleological, functional, historical) explanations, although, as Varela argued quite some time ago (Varela, 1979), it is not a question of one kind of explanation being better than the other, but rather a question of not confusing the two kinds.

But Maturana and Varela's ideas have had an impact far beyond theoretical biology. Maturana originally conceived his framework as providing a way of understanding the biological roots of cognition, and Varela's subsequent elaborations of these ideas, coupled with direct engagement with other forms of human knowing such as phenomenology, have given rise to an increasingly influential approach to cognition known as *enaction* (Varela et al., 1991; Thompson 2007). Core enactive concepts include the notions of *autonomy*, *operational closure*, *precariousness*, *adaptivity*, *agency*, and *sense-making* (Di Paolo 2005, 2009; Di Paolo and Thompson 2014; Thompson 2007). As these ideas are applied to increasingly diverse domains, from psychology and psychiatry to ethics and the arts, the enactive approach itself continues to evolve, and its core concepts change and broaden as they are confronted with new problem areas that they were not originally intended to address. This leads to a certain fluidity in the core concepts that raises both scientific and pedagogical challenges for the further development of enaction.

The central goal of this paper is to initiate a research program aimed at elucidating the theoretical foundations of enaction as clearly and rigorously as possible. Specifically, we seek to clarify the core concepts of enaction, addressing ambiguities in these concepts as they are currently conceived, drawing previously unnoticed distinctions, and in general moving towards a more formal theoretical foundation. It is especially important to unpack the core concepts in a way that transcends their origins in biological individuality so that they are meaningfully applicable to the full range of phenomena that enaction seeks to encompass, including sensorimotor and social individuality. Thus, theoretical development needs to concurrently engage the epistemic virtues of open-mindedness and conceptual rigor so that concepts may

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grow without being misapplied. These efforts are considerably aided by the operational character of the core concepts. Significant progress along these lines has already been made for Maturana and Varela's original Biology of Cognition framework (Beer, 2014, 2015, 2020b, 2020c) and we hope to extend this progress to enaction.

Our method for theory development involves the use of toy models (Di Paolo, Noble & Bullock, 2000; Beer and Williams, 2009; Reutlinger, Hangleiter & Hartmann, 2018). Toy models are highly simplified theoretical constructs that attempt to make explicit only what are thought to be the central features of a phenomenon of interest while discarding all other details as (temporarily) irrelevant. Such models serve to examine the scope and coherence of theoretical ideas and help reformulate conceptual boundaries and clarify ambiguities. They also help test the operational character of key ideas if they can indeed be implemented in a model. Toy models can serve not only as intuition pumps, but also theory pumps that often play an essential role in the early stages of theory development. At their most successful, such as the Ising model of phase transitions in statistical physics, toy models can pave the way for a more general theory from which the toy model can eventually be rederived as a special limiting case. But at the very least, they can be used to rigorously explore conceptual issues, test formalizations of theoretical concepts, and identify and/or build the necessary mathematical and computational tools for working with such theories (Beer, 2020d). Of course, such idealized models are not intended to compete with more realistic, empirically-driven models, let alone as literal instantiations *in silico* of all the complexities involved in the realization of living organisms in the real world. Rather, their only purpose here is to provide a concrete illustration of the conceptual analysis we undertake in this paper.

Perhaps the most fundamental concept in enaction is that of *autonomy*, a concept that Varela (1979) first proposed as a kind of generalization of autopoiesis that would be applicable to a wider range of phenomena than biological individuality. Indeed, in the same way that autopoiesis serves as the foundation for the Biology of Cognition framework, autonomy serves as the foundation for the enactive framework. As it is currently conceived in enaction, autonomy consists of two components: *operational closure* and *precariousness*. Operational closure describes the organization of a network of mutually supporting processes such that each process in the network is enabled by other processes in the network and, in turn, each process in the network enables some other process(es) also in the network.[1] Examples include autocatalytic systems of chemical reactions and living cells. But operational closure admits more abstract types of relations than those already covered by autopoiesis, such as the network of chemical affinities in the immune system or the self-sustaining patterns of neural firing modulated by sensory activity that one finds in the nervous system. Note that, contrary to what the term "closure" might suggest, an autonomous system remains structurally coupled to its environment and open to exchanges of all kinds; it is not self-isolated. Rather, the term "closure" is intended in the algebraic sense of a set of objects being closed under a given set of operators. A preliminary account of operational closure within the same toy model that we study in this paper has been published previously (Beer, 2015, 2020c) and we will assume that account here.

In this paper, we focus on the other component of autonomy, precariousness, which has not yet been given a systematic theoretical treatment in the literature. The paper is organized as follows. In the next section, we provide an overview of the history and current conception of the notion of precariousness in enaction. Next, we introduce the particular toy model we employ in our analysis and briefly summarize our account of operational closure within this model. The following three sections then propose a sequence of three readings of the term "precariousness", using the toy model to guide our analysis and drawing connections with other models in the literature. The paper ends with a summary of our current understanding of precariousness in light of this analysis, a discussion of various issues raised by this analysis, and some suggestions for future work.

2. Precariousness in enaction

In its modern dictionary definition, the word "precarious" refers to circumstances that are not secure and in danger of collapsing at any moment. Roughly speaking, it is a synonym for unstable or fragile. For example, a vase might be placed precariously on the edge of a high shelf, or a democracy might be at a particularly precarious moment in its history. The more technical notion of precariousness employed in the enactive approach arose slowly over time, reaching its current form only relatively recently. In this section, we briefly review the history of this core concept of enaction and present its modern definition.

In contrast with comparatively robust physical systems, such as a stone, living organisms are constitutively fragile. There is no life that does not face the ever-present possibility (in most cases the certainty) of its eventual termination. This fact was recognized very early on, at least in general terms. In their earliest writings on autopoiesis, Maturana and Varela (1980) describe how an autopoietic system loses its identity through disintegration if it encounters perturbations for which it is unable to compensate. Although they offered no further elaborations on this point, the ever-present possibility of disintegration forms an implicit background against which the remainder of the Biology of Cognition framework was constructed. Likewise, Varela's own subsequent writings (Varela, 1979) and the first presentation of the enactive framework (Varela et al., 1991) adopted a similar perspective on fragility without further elaborations. However, in later work, drawing inspiration from Hans Jonas for whom the metabolic mode of existence was inherently precarious (Jonas, 1966), Weber and Varela (2002) make a few references to the precariousness of life in terms of an organism's need to avoid perishing and the teleological orientation this need implies. This connection is further elaborated in Di Paolo (2005), where the precariousness of metabolism is discussed in order to complement the idea of autopoiesis with the concept of adaptivity as the joint conditions of possibility of agency and sense-making.

In parallel with these developments in the enactive approach, another line of work focused more explicitly on the implications of thermodynamic constraints for biological organization and on the philosophical import of precariousness more generally. There is no question that Maturana and Varela recognized the importance of thermodynamic considerations, but they held them to be secondary features. For example, they wrote "Although indeed energetic and thermodynamic considerations would necessarily enter in the analysis of how the components are physically constituted … these considerations do not enter in the characterization of the autopoietic organization. If the components can be materialized, the organization can be realized; the satisfaction of all thermodynamic and energetic relations is implicit." (Maturana and Varela, 1980, p. 89). Indeed, a number of authors have argued that autopoietic theory entails a separation between *matter* (energetic and material requirements for life) and *form* (the autopoietic organization as such) (see e.g., Fleischaker, 1988; Moreno and Ruiz-Mirazo, 1999; Ruiz-Mirazo and Moreno, 2004; Moreno and Mossio,

[1] Throughout this paper we use the terms enablement and constitution in the sense introduced by De Jaegher et al. (2010) and further elaborated in De Jaegher et al. (2016). An enabling condition for a given phenomenon is one that materially is required for the phenomenon to occur. We refer to the set of all enabling conditions as the "support base" or "enabling base" for a phenomenon. An enabling process for X is one that satisfies an enabling condition for X. Note that several processes may satisfy a given enabling condition in a redundant manner. A relation of constitution is stronger in that it involves logically entailed aspects of the conception of the constituted phenomenon. For instance, rising in the air above the ground without a supporting base is constitutive of the concept of "flying" (and of "hovering", "floating", "jumping", etc.; additional constitutive relations are needed to differentiate between these cases) while achieving this by flapping wings is a process that enables flying.

2014). Further, they suggest that this view is misleading in that biological organization remains abstract and independent of its material realization. In contrast, by taking thermodynamics seriously, biological organization becomes concretized in terms of energy management (internal energy "currencies" enabling self-construction and repair, work and heat dissipation, etc.) and temporality (kinetics of biochemical reactions, synchronization of multiple metabolic processes, and so on).

The relevance of precariousness in articulating the relation between various enactive ideas is more explicitly stated by De Jaegher and Di Paolo (2007, 487): an "[a]utonomous system is defined as a system composed of several processes that actively generate and sustain an identity under precarious conditions … By *precarious* we mean the fact that in the absence of the organization of the system as a network of processes, under otherwise equal physical conditions, isolated component processes would tend to run down or extinguish." This idea concerns the fragility of the underlying processes that constitute a living organism. More specifically: "Precarious circumstances are those in which isolated constituent processes will tend to run down or extinguish in the absence of the organization of the system in an otherwise equivalent physical situation. In other words, individual constituent processes are not simply conditioned (e.g., modulated, adjusted, modified, or coupled to other processes) but they also depend for their continuation on the organizational network they sustain; they are enabled by it and would not be able to run isolated" (Di Paolo 2009, 15).

This remains, with some minor nuances concerning timescales, the current understanding of the idea of precariousness in the enactive approach. For instance, in their Glossary, Di Paolo et al. (2018, 331) define precariousness as follows:

Precariousness: A property of nonlinearly fluctuating material relations in far-from-equilibrium systems by which no single aspect of an isolated constituent process of the system is long-term stable at the same timescale as that of the whole system. This includes any putative functional properties. Precarious circumstances in an operationally closed system are those in which its isolated constituent processes will tend to run down or extinguish in the absence of the organization of the system in an otherwise equivalent physical situation.

Precariousness is now acknowledged to play a crucial role in the enactive approach (Colombetti 2014; de Haan, 2020; Fuchs 2018; Thompson and Stapleton 2009; Di Paolo et al., 2017, 2018). Accordingly, the "added requirement of precariousness is essential in order to make the idea of operational closure non-trivial" because "[e]ach process must be prevented from decay by the activity of other processes whose operation is affected by the specific way in which they themselves are prevented from decay. In having to act against the natural tendencies of its own material support, a precarious autonomous system must produce a proper self-positing response to these tendencies" (Di Paolo 2009, 16).

Two further remarks concerning precariousness in this context are worth noticing. The first concerns the hint that life is inherently restless: An adaptive "response does not just happen to require material resources (as is the case of all far-from-equilibrium systems), but it's very form depends on the specific material precariousness it is fighting against" (ibid.). In other words, if an organism is precarious the very processes that sustain it are also a source of tendencies towards its dissolution, over and above the demands placed on its viability by the environment. This is because each process, were it to be left to run its course unaffected by other processes in the network, would eventually break the condition of closure by ceasing to exist due to its precariousness. The other observation concerns the impossibility of capturing precariousness as a functional property as would be required by a functionalist account. This is because precariousness fulfils neither the material nor the logical conditions for the concept of function. Materially, precariousness entails that any stable support for functionality (e.g., sufficiently steady distribution of states) is fragile, this includes the material conditions for the support of any putative functionality of precariousness itself. Logically, there is no utility that may be assigned to precariousness in the same sense that a function must contribute to the fulfilment of a particular, normatively defined goal. Precariousness concerns all of the inherent tendencies and the contextual conditions that can make a system as a whole lose its integrity. "Precariousness does not refer to a positive material property that could be captured functionally, but to the impermanence of any relevant positive property of the substrate" (ibid.).

3. A toy model

In previous work, Conway's Game of Life (GoL) was proposed as a toy model for exploring various conceptual issues in autopoiesis, the biology of cognition, and enaction (Beer, 2004). GoL is a 2D binary cellular automaton whose time evolution is governed by a single universal law that is local in both time and space. We will think of this law as specifying a kind of physics – the *Conway physics* – which, while differing quite substantially from "real" physics, nevertheless defines a universe whose physics, chemistry, biology, and psychology we can explore. This kind of fundamental toy model offers a significant advantage over more phenomenological models which attempt to directly engage the relevant chemical or biological phenomena and are therefore forced to postulate many arbitrary details (e.g., molecular species and reaction kinetics for a chemical model, or sensor and effector capabilities for an organismal one). In contrast, we specify only one arbitrary detail: the Conway physics. Everything else is derived rigorously from that.

The Conway physics can be written compactly as

$$\mathbf{U}_{t+1} = \boldsymbol{\delta}_{\boldsymbol{\Sigma}[\mathbf{U}_t],3} + \mathbf{U}_t \odot \boldsymbol{\delta}_{\boldsymbol{\Sigma}[\mathbf{U}_t],2},$$

where $\mathbf{U}_t$ denotes the 2D discrete binary field defining the state of the GoL universe at time t, $\boldsymbol{\Sigma}$ is a spatial operator that gives the Moore neighborhood count field of a discrete binary field, $\boldsymbol{\delta}$ denotes a field-oriented Kronecker delta function, and $\odot$ denotes the Hadamard (element-wise) product of two fields. In words, this law states that a site will be ON in the next generation only if (1) it is surrounded by three other ON sites, or (2) it is currently ON and surrounded by two other ON sites. Otherwise it will be OFF.

From the Conway physics we can derive a simple spatial chemistry in which local arrangements of 0- and 1-components "react" to produce new arrangements. Several kinds of processes can be distinguished. *Production* processes create a new 1-component, *destruction* processes destroy an existing 1-component, and *0-maintenance* and *1-maintenance* processes preserve an existing 0- or 1-component, respectively. Since the components produced by one process can serve to enable other processes, dependency relations exist between processes.

During the time-evolution of a GoL universe from random initial conditions, one observes the appearance and persistence of a variety of bounded spatiotemporal patterns. We focus here on the smallest mobile pattern in GoL: the glider (Fig. 1A). Using a formal interpretation of the concept of autopoiesis, a constitutive theory of gliders has been described previously (Beer, 2015). We first identified the processes underlying a glider. We then demonstrated how each constituent process generated products that in turn enabled other constituent processes in an operationally-closed manner, satisfying the self-production condition of autopoiesis. Then we showed that a glider possesses a boundary of 0-components that is both produced by the network of processes and required by that network for its continued operation, satisfying the self-distinction condition. A schematic representation of the glider organization that results from this analysis is shown in Fig. 1B. Technically, this figure presents only the vacuum glider organization, describing the operation of a glider in an otherwise empty universe. Although an account of the generalized glider organization (which provides a description that holds across all universes in which a glider can exist, not just the otherwise empty ones) has also been developed (Beer, 2020c), it is beyond the scope of this paper.

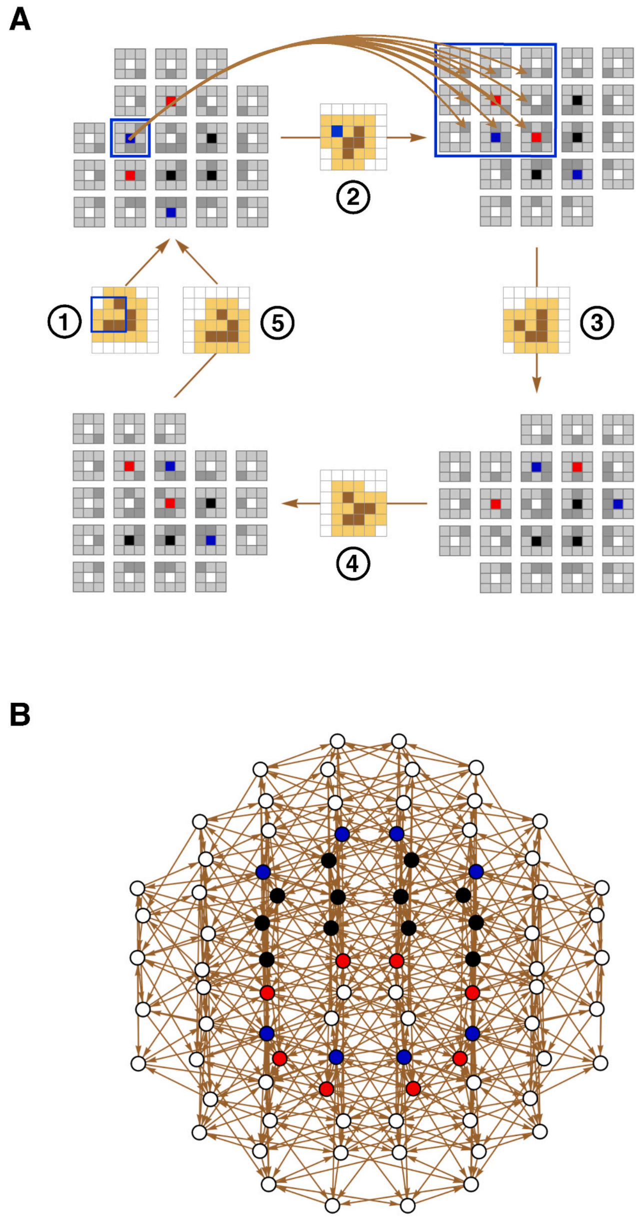

Fig. 1. The vacuum glider organization. (A) The 4-cycle that a glider repeats in an otherwise empty environment and the underlying processes that create and maintain this cycle. At each step, the current arrangement of components triggers a set of processes, which produce a new arrangement of components, which trigger another set of processes, and so on until, after four steps, the glider has moved diagonally by one grid site (compare configuration 1 to configuration 5) and the original set of processes is triggered once again at this new location. The 1- and 0-components in each glider configuration are colored brown and tan, respectively. Each process is represented as a 3×3 arrangement of sites. The color of the central site indicates the type of process (blue for a production process, red for a destruction process, black for a 1-maintenance process and white for a 0-maintenance process). The eight surrounding sites are shaded dark gray or light gray according to whether they must contain a 1-component or a 0-component, respectively, in order for that process to be triggered. The process outlined in blue produces a 1-component (filled blue square) which plays a role in triggering nine other processes (also outlined in blue at upper right). The fact that processes depend on the products of other processes induces dependency relations between processes, a few examples of which are shown as brown arcs. (B). The closed network of process dependencies that underlie the operation of a glider in an empty environment. Each node is a schematic representation of a process from part (A), colored by its type. Each arc represents a dependency relation between one process and another.

We now turn to an analysis of the ways in which a glider's operational closure can or cannot be said to be precarious.

4. Systemic fragility

The minimal way in which an operational closure can be said to be precarious is when it is *systemically* fragile, that is, when it is capable of losing its integrity as a system. If the network of processes is sufficiently disrupted that the mutually supporting organization of those processes disintegrates, the identity that network constituted is lost. Because such a unity can fail to exist at any time, it is threatened at all times with the possibility of extinction. Systemic fragility is essentially the notion that is implicit in Maturana and Varela's (1980) original formulation of autopoiesis, and it also seems to be the main sense in which Jonas (1966), Weber and Varela (2002), early Di Paolo (2005) and Thompson (2007) originally conceived of precariousness.

The idea of systemic fragility is easy to illustrate in our toy model. Imagine a glider interacting with two different environments (Fig. 2). In the first case, the glider maintains its integrity throughout the interaction despite these perturbations to its normal operation (Fig. 2A). In the second case, however, the glider is unable to compensate for this particular perturbation and it disintegrates, leaving a state of the GoL universe that follows lawfully from the previous one but that no longer contains a glider (Fig. 2B). The very existence of the glider as a system is fragile; it can disintegrate if the network of processes that support it are sufficiently disrupted. Other models that illustrate systemic fragility include those by Varela et al. (1974), Ono and Ikegami (2000), McMullin (2004), and Agmon et al. (2016). Additional models that appear to be systemically fragile include those based on partial differential equation formulations of spatial chemistry (Virgo 2011; Bartlett and Bullock, 2016; Chan, 2019). In these models, some kind of bounded, spatiotemporally-organized and persistent pattern is observed, although these patterns have not been analyzed in terms of operational closure.

Systemic fragility might seem like a rather trivial characteristic. How is it possible for an operational closure to lack systemic precariousness? At least conceptually, the two ideas are distinct. In fact, the majority of protocell models, to take one relevant case out of many, do not capture systemic precariousness because they assume the existence of the model cell a priori, with "death" only occurring when some externally-imposed condition such as a surface-volume constraint is violated (Ruiz-Mirazo, 2008). Indeed, current "whole-cell" models in biology fail to capture the systemic fragility of living cells in exactly this way (Karr et al., 2012; Macklin et al., 2020; Sun, Ahn-Horst & Covert, 2021). Other examples of models that are not systemically fragile include those by Egbert and Di Paolo (2009) and Agmon et al. (2017). In all of these models, closures exist by fiat, imposed and maintained by things external to the system rather than by the operation of the system's own constituent processes. These closures cannot intrinsically disintegrate *by definition*, although they can be terminated extrinsically once some externally-imposed condition is violated.

This leads to an interesting observation. A closure is systemically fragile to the extent that its organization is emergent from some underlying substrate. Although the general possibility of gliders in GoL are of course implicit in the Conway physics, the existence of a particular glider *here* and *now* is not given a priori; it requires the right local conditions for the closed network of process dependencies to arise and be maintained. Rather than being preprogrammed, gliders are systemically precarious because they can emerge from (and decay back into) an underlying artificial chemistry. This weak/epistemological notion of emergence is all that is necessary for our purposes here; no claim about strong/ontological emergence is required. Spatiality plays a central role here. Although one process contributing to the enablement of another is a causal and hence temporal relationship, which processes are enabled also depends on the spatial relationships among a set of precursor processes, and it is the ephemeral nature of these spatial arrangements of processes that endow gliders with their systemic fragility. Likewise, in a

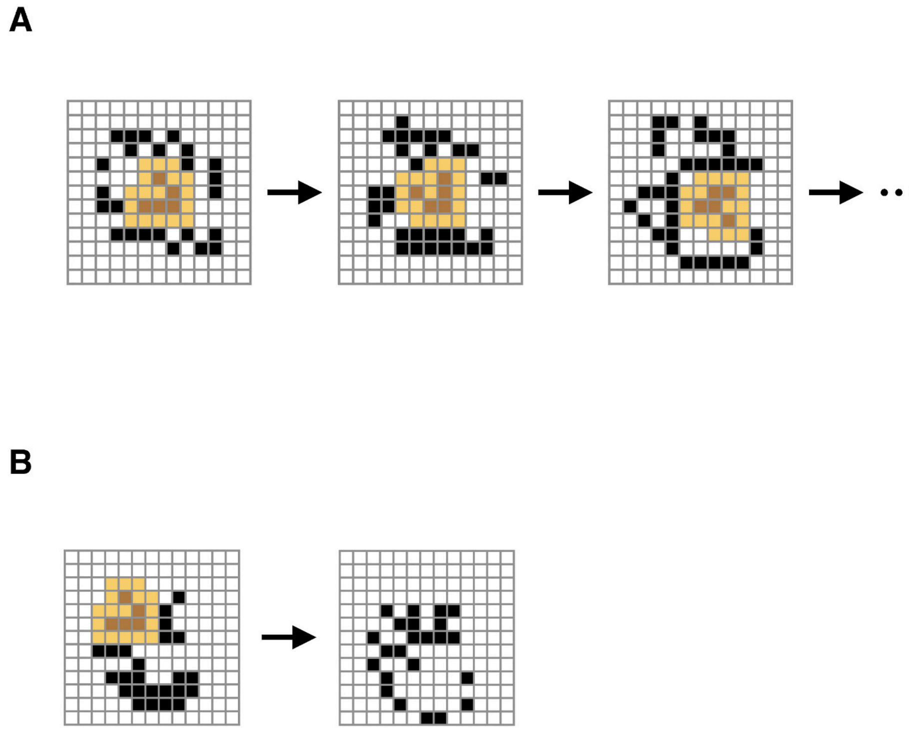

Fig. 2. An illustration of systemic fragility. (A) A glider situated within an environment in which it encounters a series of perturbations for which it can compensate, allowing the glider to persist. (B) If a glider encounters a perturbation for which it is unable to compensate, the underlying network of processes that constitute that glider loses its integrity and the glider disintegrates.

living cell, it is not merely the reactions taking place but also the spatial organization of those reactions that ensure its continued existence. This connection between precariousness and emergence is one that we will see repeated in subsequent sections.

5. Processual fragility

A second, more restrictive, kind of precariousness arises from *processual* fragility. As proposed by Di Paolo (2009), a processually precarious individual is not only fragile as a system, but the very processes whose interactions constitute that system are themselves fragile. In a merely systemically fragile individual, the organization of the individual can be lost, but its constituent processes can continue to run in isolation. Although the support base for a constituent process must include other constituent processes in the operationally closed system, it may also include enabling support from external processes that could prevent the process from running down even if operational closure is disrupted. To see this, it is important to remember that different processes may contribute to satisfying an enabling condition for a given process redundantly. In contrast, in a processually fragile system this is not the case, i.e., without the support of the network of interdependencies of the closure in which they occur, those processes will run down and disappear.

An important consideration in the way processual fragility is formulated in the enactive literature is that *all* of the processes constituting the operationally-closed network must be fragile in the processual sense. If some constitutive process remained stable in its operation regardless of what happens to any other process in the network, then any dependencies on that particular process would be guaranteed and the system could be considered as existing in a dependent fashion on an external process that is self-standing. This observation compels us to clarify what we mean by a process in each context, since we know that certain important patterns, such as the structure of DNA in biological cells, tend to be long-term stable on their own. What matters in such cases, however, is not the presence or absence of stable patterns involved in a particular process, but the process' operation and its impact on the network of dependencies, and whether these are processually fragile. The production of proteins out of stable genetic patterns depends on patterns of genetic regulation and the overall operation of the cellular machinery, which in itself counts as processually fragile. Having said all this, it is important to clarify that a process being fragile does not preclude the possibility of its being more or less robust in comparison with other fragile processes, i.e., less or more prone to change under a variety of conditions. This does not make a relatively robust process any less processually fragile if it ultimately relies for its continuation on other processes in the operationally closed network.

Once again, this idea is straightforwardly illustrated in our toy model. Consider the production process outlined in blue at the top left of Fig. 1A. This same process actually occurs a second time (with a different orientation and chirality) in the set of processes at the lower right of Fig. 1A. In the normal operation of a glider, this process is cyclically renewed. It creates a 1-component that serves as a "fin" of the "rocket" form of a glider (see the blue component in the configuration marked 2 in Fig. 1A). In turn, this 1-component helps to enable other processes that subsequently create new arrangements of components and so on until, within the closed organization of the glider, the original process is ultimately retriggered.

Of course, this same process can occur in other contexts as well (Fig. 3). However, a crucial difference here is that the cascade of enablements that follow do not serve to re-enable the original process. Instead, other processes are enabled and the entire configuration ultimately dissipates into quiescence. Without the constantly-renewing supporting organization provided by a closure, individual processes run down and extinguish. Hence, a glider illustrates not only systemic fragility, but also processual fragility.

Just as systemic fragility is only possible in a context in which the

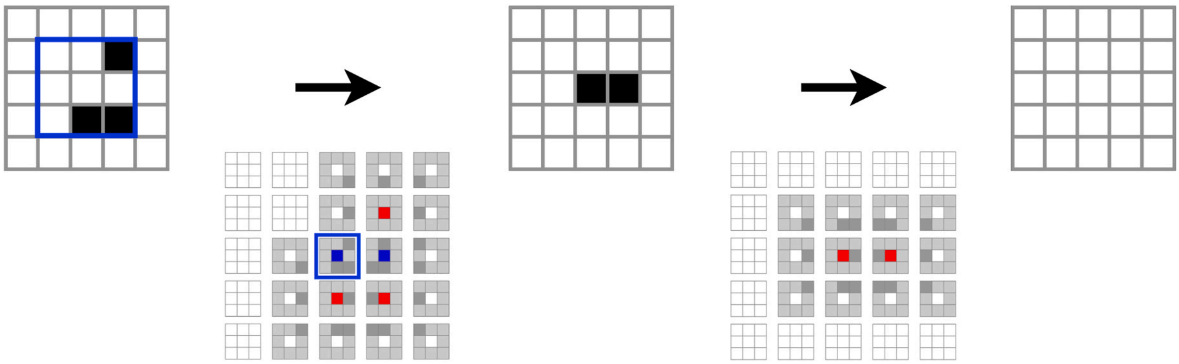

Fig. 3. An illustration of processual fragility. The production process highlighted in blue in Fig. 1 is shown in a different context. In this case, rather than being cyclically renewed as in a glider, that process triggers different processes that ultimately result in the entire configuration decaying to quiescence.

network of process interdependencies is emergent and can thus disintegrate, processual fragility is only possible in a context in which the underlying processes themselves are also emergent. In GoL, this occurs because it is the underlying physics which is hardwired into the universe, not the chemistry. This allows processes to arise and extinguish at different locations over time.

There are few other models that capture this strong form of processual fragility. One notable early example is Fontana's AlChemy (Fontana, 1992; Fontana and Buss, 1994), in which functions in the λ-calculus (represented as LISP expressions) are repeatedly applied to one another in a kind of computational reaction vessel, sometimes producing closed, self-maintaining networks of functions. Since at least one of the "reactants" is always used up, the constituent functions themselves will disappear without the support of the operational closure in which they are a part. Interestingly, spatiality plays no role in this model. A related approach that is more chemically-grounded is chemical organization theory (Dittrich & di Fenizio, 2007).

What about models based on partial differential equation formulations of spatial chemistry which we discussed above as examples of systemic fragility (Ono and Ikegami, 2000; Virgo 2011; Agmon et al., 2016; Bartlett and Bullock, 2016; Chan, 2019)? In these cases, the reactants and the reactions they participate in are fixed by the partial differential equations which define the models. Thus, there is no sense in which these processes are emergent and hence such models do not capture processual fragility in the strongest sense. However, because the reactants in these reaction-diffusion models can "run down" to zero concentration without the support of the (identical) surrounding reactions, primarily due to the diffusion term, these pregiven processes have essentially stopped doing anything. Thus, we might consider this family of models to capture a weaker form of processual fragility in the way processes operate and influence one other. This suggests that, as with the other forms of fragility we consider, processual fragility is not a monolithic concept, but presents some degree of complexity and shades of interpretation, which often depend on the research question and the way the observer approaches the system under study.

6. Thermodynamic fragility

Another more restrictive kind of precariousness can arise when operational closures are physically instantiated: *thermodynamic* fragility. Thermodynamically fragile operational closures are those whose very form is dependent on thermodynamic conditions. For instance, if the organization requires strict temporal relations between processes that depend on reaction rates, or energy flows, etc. The spatiality and temporality of the organization in such cases is in part defined by the thermodynamic constraints and conditions. Change these conditions and some processes may slow down, some patterns may disappear, etc. and this particular operational closure will cease to exist. The system's organization is therefore fragile with respect to thermodynamics.

Of course, all systems are ultimately physically-realized systems in some way (even if they only exist as patterns of neural activity in someone's brain, or as mathematical equations on a piece of paper, or as programs in a computer) and thus ultimately subject to thermodynamic constraints. But in many cases thermodynamics enters only as an implicit background assumption, in much the same way that, say, particle physics does. The standard model of physics underlies all of chemistry, for example, but it plays no explicit role in chemical theories. Likewise, operational closures that arise in sensorimotor or social interaction (De Jaegher and Di Paolo 2007; Di Paolo et al., 2017), while obviously ultimately subject to thermodynamic constraints, are not necessarily thermodynamically fragile according to our definition. However, in other cases, such as living systems, thermodynamic considerations play an essential role, since the very organization of living systems is shaped by their need to resist the second law. It is only in this latter case that we consider an operational closure to be thermodynamically fragile. Otherwise, the notion of a thermodynamically precarious system would be tautological.

It is immediately apparent that gliders in GoL are not thermodynamically fragile in this sense. The Conway physics does not exhibit a realistic thermodynamics. Although deterministic, it is neither reversible nor conservative, and does not possess conserved quantities like energy. But more fundamentally, a glider is self-supporting; it does not require any external flows of material or energy to persist and its form is not specifically organized so as to shape such flows in order to resist thermodynamic degradation. Thus, our toy model certainly does not provide a complete model of thermodynamic fragility.

However, it is interesting to note that the toy model does exhibit some aspects of thermodynamic fragility. For example, GoL possesses an equilibrium state (quiescence) to which almost all configurations decay unless actively resisted by special organizations of processes. Indeed, GoL has frequently been studied from the perspective of statistical mechanics (Schulman and Seiden, 1978; Bagnoli et al., 1991; Adachi, Peper & Lee, 2004). Furthermore, one can find GoL patterns that only persist in the presence of structures in the environment on which they can "feed". For example, in the Driven Game of Life (Beer, 2020a), new persistent structures arise when selected grid sites are externally held ON or OFF in particular patterns (Fig. 4a). One could likewise imagine an operational closure that, unlike a glider, *requires* some interaction with other patterns which it must regularly consume in order to persist (Fig. 4b), although we have no such examples to offer at present. Finally, the fact

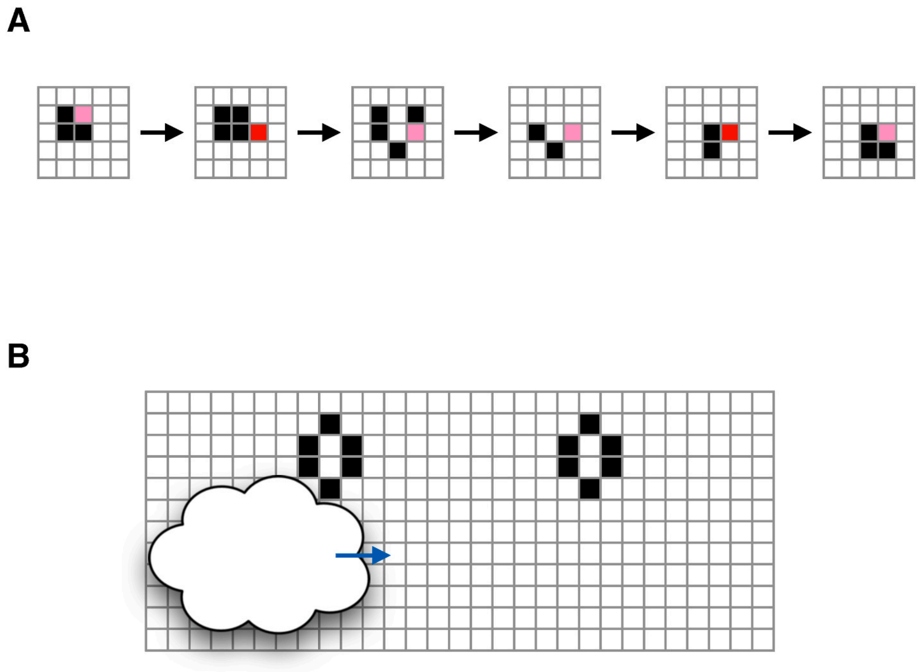

Fig. 4. Partial illustrations of thermodynamic fragility. (A) An example of an entity that appears in the Driven Game of Life when a single site (colored) is externally held ON for five time steps before moving one position diagonally and once again held ON for five time steps. The externally-driven site is colored pink when its ON status is supported by the Conway physics and red when it is only the external drive that is holding it ON. If this external drive is withdrawn, this closure will either disintegrate or stabilize into a stationary block depending on the timing of withdrawal. (B) A schematic illustration of a hypothetical rightward-moving entity in the standard Game of Life that requires regular interactions with particular organized structures in order to persist. The cloud represents the (currently unknown) configuration of ON and OFF sites that constitute this entity and the diamond-shaped patterns (known as "beehives" in GoL parlance) represent structures upon which it must regularly "feed" to maintain its operational closure.

that the Conway physics is inherently dissipative[2] (pattern formation occurs naturally in GoL without having to work – both figuratively and literally – for it as in the physical world) might be argued to be a virtue rather than a drawback for a general theory of autonomy rather than merely a theory of its physical instantiation. Of course, it would be interesting to explore the possibility of slightly complicating something like the Conway physics to capture more thermodynamic realism.

Thermodynamic fragility can only be exhibited fully in a context in which patterns of energy flow are emergent rather than pregiven and can thus collapse if they are not properly maintained. A glider fails to be thermodynamically fragile precisely because it does not suffer this threat. In a sense, a glider exists against an assumed background of energy flows which enable the illusion that its underlying processes run for free (this is literally true when GoL is implemented on a computer, whose own energy source supports that illusion). In contrast, a thermodynamically fragile system operates under no such illusions and its organization is explicitly concerned with managing the necessary energy flows.

To our knowledge, no computational model of operational closure thus far has fully captured this kind of precariousness. It is not yet clear what sort of underlying substrate might be required to do so; it may require that dissipativity itself be emergent from an underlying conservative substrate driven from thermodynamic equilibrium. Perhaps the models that come the closest are those based on reaction-diffusion spatial chemistries (Ono and Ikegami, 2000; Virgo 2011; Agmon et al., 2016; Bartlett and Bullock, 2016; Chan, 2019). Due to the diffusive terms in these models, the organized structures that they exhibit will disintegrate without the reactive component of the model. However, the dissipative character of these models is built-in to the nondiffusive terms in their partial differential equations rather than arising from an underlying conservative dynamics. Furthermore, although in some of these models an explicit flow of external energy and/or matter is required to maintain the pattern-forming reactions (Virgo 2011; Agmon et al., 2016; Bartlett and Bullock, 2016), in others this flow is merely assumed (Ono and Ikegami, 2000; Chan, 2019). The form of the energy flow in these models is also prescribed rather than emergent. Indeed, in that sense, the dissipative structures exhibited in these latter models are no more thermodynamically fragile than is a glider in GoL. Note that these statements are in no way intended as a criticism of these models, but merely an attempt to classify them according to the distinctions introduced in this paper. Thus, as for processual fragility above, we find not a monolithic concept, but rather degrees of thermodynamic fragility.

Perhaps the best context in which to clarify the nature of thermodynamic constraints, at least for the case of biological individuality, is the very active and interesting approach of in vivo construction and analysis of chemical model systems exhibiting life-like characteristics (e.g., Luisi, 2006; Hanczyc et al., 2007; Hanczyc, 2011; Hardy et al., 2015; Engwerda et al., 2020). In this case, the far-from-equilibrium conditions under which such model systems operate, and the constraints this places upon the form of their operational closure, are manifest. Note, however, that such model systems do not allow one to address our broader question of how to interpret the concept of precariousness for general autonomous systems.

7. Discussion

Given the tremendous interest in and growth of the enactive approach to cognition in recent years, we believe that its core concepts would benefit from more systematic theoretical foundations. In this paper, we have taken some initial steps toward unpacking one of those core concepts, precariousness, using a toy model to concretize our dissection of the various issues involved. Our goal has been to characterize the possible meanings of the phrase "under precarious conditions"

[2] In dynamical systems theory (of which classical mechanics is a special case), a system is conservative if state space volumes are preserved under the flow, and dissipative if state space volumes contract under the flow. It is only dissipative systems that can exhibit attractors, i.e. robust patterns. In physics, these terms have a more specific meaning because they are historically attached to the particular way in which a conservative physical system can become dissipative. In a Hamiltonian system, the conserved quantity represented by phase space volume is energy. If the system is closed, then eventually this energy comes to be equally distributed across all degrees of freedom in the system (thermodynamic equilibrium) and no robust patterns can be formed. In contrast, if the system is open to flows of high-quality energy then it can be driven out of thermodynamic equilibrium into regimes where robust patterns can form, producing heat in the process. This is called "dissipating energy" in physics.

that appears frequently in the enactive literature. Specifically, we have proposed that at least three readings of "precariousness" can be identified according to the particular way in which a given operational closure (OC) is fragile, and, further, that each type of fragility is characterized by a particular kind of emergence. A systemically fragile OC is simply one that can disintegrate. Systemic fragility arises when the organization of an OC is emergent from an underlying medium. A processually fragile OC is one whose constituent processes disintegrate in the absence of the mutual support of the larger organization. Processual fragility arises when the processes themselves are emergent from an underlying substrate and can hence decay back into that substrate without the proper maintenance. Finally, a thermodynamically fragile OC is a physically-realized closure whose very form is dictated by thermodynamic considerations. It arises when patterns of energy flow are emergent from an underlying medium.

What is the relationship between these three kinds of fragility? The situation as we currently see it is illustrated in Fig. 5. The weakest form of precariousness is systemic fragility, which is thus co-extensive with precarious OCs and hence autonomous systems. Processual fragility forms a strict subset of systemic fragility. One way for a system to be fragile is if its constituent processes are, but that is not the only way. For example, if the network of enabling relations is disrupted but the processes themselves continue on individually, then the OC is systemically fragile but not processually so. Another strict subset of systemic fragility is thermodynamic fragility. Although enaction has tended to treat far-from-equilibrium thermodynamics as a core concept, we have suggested that, while it may be fundamental for some autonomous systems, it is not necessarily fundamental for all. The determining factor is whether or not the form of the operational closure itself (and not just its material implementation) is dependent upon thermodynamic considerations. Finally, the relationship between thermodynamic and processual fragility is not yet settled. Clearly they overlap. Indeed, we expect that most thermodynamically fragile OCs will also be processually fragile. However, whether thermodynamically fragile OCs that are not processually fragile exist remains an open question, depending to a large extent on how one chooses to define the notions of process and enabling relation.

Consider for example an autocatalytic network of chemical reactions, bounded in an enclosure and subject to a flow of matter and energy. Here the OC network is constituted by chemical reactions R_n operating at rates r_n whose values must be within some viable range for the whole network to exist. The rate r_n is determined by the physical conditions and by the presence of catalysts C_x, themselves products of

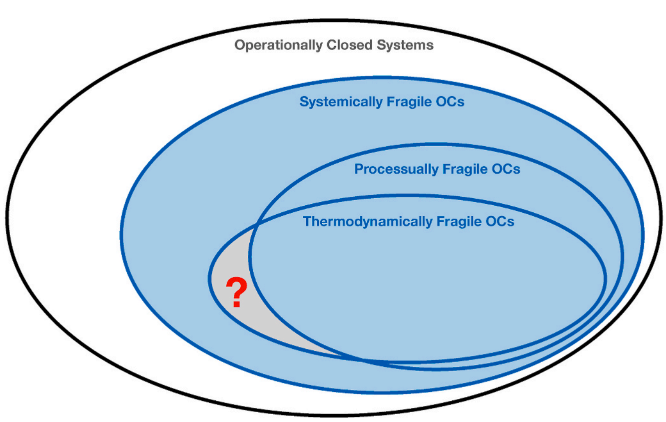

Fig. 5. A Venn diagram of the decomposition of precariousness proposed in this paper. Our universe of discourse is operationally closed (OC) systems. A subset of OCs are precarious and hence autonomous (indicated in blue). All precarious OCs are systemically fragile, but only some are processually or thermodynamically fragile. Whether or not there exist thermodynamically fragile OCs that are not processually fragile remains an open question (gray region with question mark).

other reactions in the OC network. In general circumstances we would expect a process, i.e. a reaction R_n operating at a viable rate r_n, to be itself fragile, in other words, to depend on the presence of the rest of the OC network, even under otherwise identical physical conditions. But it is possible to conceive of a reaction R_1 that is influenced by a catalyst C_1 and an inhibitor C_2 with opposite effects—one accelerating the reaction, the other slowing it down—with the net result that R_1's rate is not different from the "natural" rate of this chemical reaction outside the OC network. In such a case, R_1 is a process belonging to the network that is itself not processually fragile even if it is thermodynamically fragile (i.e., remove the rest of the OC network and the process will continue unchanged under the same thermodynamic conditions). The example may seem contrived, but it is not inconceivable that such a rein-controlled process (Clynes 1969; Saunders et al., 1998) might operate as a kind of internal "signaling" system with the products of R_1 indicating the relative concentrations of C_1 and C_2 and that, in terms of efficiency, the operating range of r_1 should match that of the external environment. This thought experiment demonstrates why the precise relationship between thermodynamic and processual fragility requires further analysis.

Although our focus in this paper has mostly been on biological autonomy, we fully expect the distinctions between various kinds of fragility that we have introduced to apply to other forms of autonomy as well. In the sensorimotor case, for instance, it has been suggested that patterns of activity in the form of mutually supported sensorimotor schemes can, in certain conditions, give rise to identifiable closed organizations such as habits (Di Paolo et al., 2017). These habits involve mutually enabled patterns of coordination between body and environment that are history-dependent and establish the conditions for their renewed and repeated enactment. Being history-dependent suggests these patterns are systemically fragile, i.e., they are neither prescribed nor guaranteed to occur. However, not all processes involved in the enactment of a habit need themselves be always fragile. The habit of going for a short walk in the morning followed by breakfast involves a particular organization of schemes (walking, coming home, preparing breakfast, drinking, eating) that themselves will likely continue to exist independently should this organization ever be disrupted. Other habits might involve a tighter integration between component schemes, as in the case of developing an addiction to outdoor exercise or, less healthily, a substance addiction. At some point of development in these cases, the why and wherefore of each component scheme is to be found in the rest of the habit's organization. The distinction between systemic and processual fragility, therefore, remains useful in the sensorimotor case. We expect that this is also true in other forms of closure as in the case of social interaction and participatory sense-making (De Jaegher and Di Paolo 2007) where the component processes are patterns of coordination and mutual perturbation between participants that can take different "degrees" of co-dependence, from mere orientation to joint meaning-making.

As these wider forms of autonomous dynamics operate in the real world, they will be influenced by thermodynamic constraints. This does not immediately make them thermodynamically fragile, however. For instance, patterns of social interaction mediated by written communication technologies (e.g., letters, email, chats) may develop a history of mutually supporting meaning-making processes, which, while physical, can show a more extended viable temporality than we would expect from the energetics involved in the component processes. This temporality (for instance, the polite time to offer a response to a question via email) follows norms that are appropriate to the activity itself and are constrained but not prescribed by the thermodynamics of the interaction. In the sensorimotor case, non-dissipative structures such as solid objects may enter into the organization of habits as in the case of the skillful use of a cane by a blind person to avoid obstacles, raising the non-trivial question of whether the whole sensorimotor organization is in this case thermodynamically fragile.

We believe that the toy modeling approach we have taken in this paper has a key role to play in the further theoretical development of enaction. Models, even toy ones, help ground debates that can otherwise deteriorate into dueling intuitions. By their concreteness and simplicity, toy models can force us to confront subtleties that are easily missed in verbal debate, not only revealing deeper insights into the phenomena of interest, but also providing a vehicle for the development of the necessary conceptual and, eventually, mathematical tools for their rigorous characterization. Of course, it is important to emphasize that toy models are not intended to serve as realistic models of the phenomena they target. They are tools for thinking. They are also not intended to be literal instantiations of those phenomena. No one dismisses a model of an airplane because the model itself does not fly, or a model of a storm system because it does not make you wet. Likewise, models of enaction do not themselves have to be alive, or autonomous, or precarious in order to illuminate these core concepts of enaction.

The intention of this paper is to start a conversation, not to end one. We certainly do not believe that we have written the final word on the notion of precariousness in enaction. Many questions remain. What are the precise relationships between the subsets of precariousness that we have identified, especially for the case of thermodynamic fragility? How best to characterize the variations of degree that we sometimes find within these classes? Are there other important subclasses of precariousness that our analysis has missed? How might we extend the Conway physics or construct another more thermodynamically realistic toy model so as to more fully explore the subtleties of thermodynamic fragility? Finally, a major direction for future work is to continue clarifying the theoretical foundations of enaction by expanding the approach we have followed in this paper to other core concepts of enaction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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