

Everything Flows: Towards a Processual Philosophy of Biology

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Biological Processes

Criteria of Identity and Persistence

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Abstract and Keywords

This chapter investigates the identity and persistence conditions for processes as a task of biological process ontology. It argues that the problem of intrinsic variation in evolution, development, and metabolism motivates viewing biological individuals as processes rather than as substances. Different criteria of identity for processes are then evaluated, including causal and spatio-temporal relations. The chapter ultimately settles on the view that processes are individuated by causal cohesion and are identical if they share the same cohesive properties and spatio-temporal region. The persistence of processes is interpreted on the model of perdurance, as a form of causal continuity or genidentity.

Keywords: biological process, causal cohesion, criteria of identity, essentialism, genidentity, individuality, persistence, process ontology, substance ontology

1. Introduction

The life sciences have long described biological systems as being fundamentally dynamic at all scales, from the evolution of species to the developmental construction of individuals to the continual energetic turnover of metabolism. There has historically been a variety of attempts to motivate a shift in ontology on the basis of the empirically dynamic character of the biological world. Something like ‘process ontology of biology’ was advanced by many of the organicist philosophers of biology of the twentieth century who came under the influence of Whitehead and Bergson—notably Woodger (1929) and von

Bertalanffy (1952); and it has also been suggested by Waddington (1957), by process structuralists like Webster and Goodwin (1996), by the plant morphologist Sattler (1990, 1992), and by Bickhard (2009), Jaeger and Monk (2015), and Dupré (2012)—among others.

Scepticism toward this type of project, such as there is, is less likely to be directed at the biological facts that have inspired it than at the claim to constitute a novel ontology that rivals more traditional ontological frameworks in descriptive richness and explanatory scope. Accordingly, this chapter aims to advance the underdeveloped ontology of individual processes. I focus on explicating what are arguably the two most important categorial features of biological processes—their persistence and their identity or individuation conditions—in contrast to their substance-ontological counterparts. The process ontology I defend is committed to providing a causal account of biological persistence and individuation—a commitment that underlies its advantages as well as its distinctive challenges.

2. Ontological Explanation for Scientific Domains

Before examining the aspects of contemporary biology that motivate a processual perspective on life, first it will be necessary to clarify how an ontology can be ‘motivated’ by a scientific field at all. What basis is there for choosing between a process-based and a substance-based ontology in the context of biology?

Ontological theory choice can be helpfully understood by analogy with scientific theory choice. Scientific theories are typically evaluated on the basis of a cluster of (p.77) epistemic virtues such as predictive power, explanatory power, unity with other accepted theories, simplicity, and so on. The analogy begins to pull apart on the issue of predictive power, but otherwise it is relatively uncontroversial that one ontology can be simpler than another, more consistent, or more globally unified than another, and that these are desiderata for ontological theories. The epistemic virtue that I highlight, however, which is less well understood, is explanatory power. Rival ontologies can provide better or worse ontological explanations, and it is primarily here that they can come into contact with scientific theories.

To clarify the notion of ontological explanation, we should consider what an ontology for a given scientific domain is supposed to do. The dominant approach to ontology in the analytic tradition, the one initiated by Carnap (1949) and Quine (1939), aims to extract ontological commitments from a language that governs a given domain by examining the wide-ranging structural inferences comprised in the language. Starting from the structure of the language, one can then develop an ontological theory of its domain by providing a systematic account of the truth makers for its sentences. Different ontologies for the same

domain differ by offering contrasting descriptions of what it is in virtue of which the true sentences of the language are true.

The sense in which contrasting ontologies can differ as to their explanatory power is characterized by Seibt (2008, 2010, 2015) as follows. In providing a description of truth makers for sentences of a language, an ontology explains why we are justified in drawing certain 'categorical inferences' from these sentences. Consider the following true sentences:

- (1) This tree is green.
- (2) This is the same tree as the young sapling you saw last year.

An ontology explains, for instance, why one is justified in inferring from (1) that the denotation of 'green' can occur multiply in space whereas the denotation of 'this tree' cannot (Seibt 2008). Many items can be green but only one thing is this tree. An ontology might explain this inference by postulating that a tree is a substance, having the category feature of particularity, that is, having unique spatio-temporal location necessarily. By contrast, 'green' denotes a property or universal that can be multiply instantiated in space and time. Such a theory explains successfully, due to the fact that the theoretical terms 'substance' and 'universal' properly fulfil certain categorial-inferential roles that are fixed by accepted facts about trees—that is, that distinct trees can each be green. Similarly, an ontology explains why a speaker is justified in inferring from (2) that 'young sapling' and 'this tree' are co-referential by categorizing the tree as an individual substance. Invoking the ontological category of substance can explain why the inference is justified, because substances have the category feature of numerical identity over time, so that the young sapling is one and the same thing as the tree presently being observed.

In constructing an ontology specifically for a scientific domain, the categorial-inferential roles are set by the established contents of theories and models in that science. Different categories can fulfil these roles better or worse, and this leads to differences in the explanatory power of the associated ontologies. For example, there is pressure from developmental and evolutionary biology to be able to say that (i) an **(p.78)** individual that undergoes substantial changes during ontogeny is still the same individual, whereas (ii) one that reproduces is distinct from any offspring it has. I will argue that the category of substance is too strong to play the inferential role embedded in (i), while the category of process is not. Conversely, the category of process is, like that of substance, *not too weak* to be able to play the inferential role embedded in (ii). This is a case in which a process ontology of individuals has greater explanatory power, because it can explain everything that substance ontology can explain but without occasioning problems from (i). Similarly, aspects of ecology and biochemistry suggest that we should be able to say that certain systems have weak individuality despite being spatially scattered and non-uniquely located. As I will

argue in section 4, the category of substance is also too strong here, whereas the category of process is not. If these arguments are right, then process ontology constitutes a better domain ontology than substance ontology due to its greater explanatory power.

The more acute problem for substance ontology in biology is certainly that of persistence despite change; and, as we will see in the following section, it arises due to the connection between substance ontology and essentialism.

3. An Argument for Biological Process Ontology

There are, arguably, many reasons to think that contemporary biology favours the adoption of process ontology. I will focus here on one argument for viewing biological individuals as processes, which starts from a familiar story about biological essentialism.

Before the arrival of evolutionary theory, biological species were for the most part still conceived of on the Aristotelian model of fixed kinds, or even as types corresponding to archetypes in the mind of the Creator. Darwin was able to show that the variety of species can be explained by appeal to a long-term evolutionary process of natural selection acting on heritable variations. Not only are the different species we observe today derived from common ancestors, but species kinds are themselves temporary stages in an ongoing evolutionary process. Moreover, the critical importance of variation in this process means that we should not expect intraspecific variation to be confined to variation only in the 'accidental' properties of species. Species are therefore very different from paradigmatic natural kinds such as the elements of the periodic table, because they are continually varying and evolving into new species.

Many philosophers of biology accept the arguments of Ghiselin (1974) and Hull (1978) that species do not belong to the ontological category of classes or kinds at all, but are rather historically extended individuals. On this view, an organism or a population is not an instance of a species in the way in which a piece of gold is an instance of the chemical kind gold, but is rather a part of a species in the way in which one is part of one's family lineage. This conception of species was inspired by the cladistic classification program, which sought to tie biological classifications more closely to actual evolutionary history. On the cladistic view, species are individual segments in the evolutionary tree between phylogenetic branching points. In fact matters are more complicated than a simple contrast between kinds and individuals might suggest. If species were *merely* genealogically defined segments of the **(p.79)** phylogenetic tree, it is doubtful that the cladistic classification of an organism would explain very much about it besides its position in the genealogical nexus. Like traditional natural kinds, cladistic classifications are used to identify underlying patterns of resemblance between members of groups, despite the fact that these patterns are spatio-temporally restricted in the way individuals are (see Griffiths 1994: 211). The

'species as individuals thesis' certainly does not resolve all the problems surrounding biological species, but the least one can say is that it recasts the concept of species in a more dynamic light than before. It is also an interesting example of a categorial claim that is similar in form to the one suggested here. The claim is that, within the domain ontology for evolutionary biology and systematics, species lack the category features of generality and unrestricted instantiability and are characterized instead by historical individuality and concreteness.

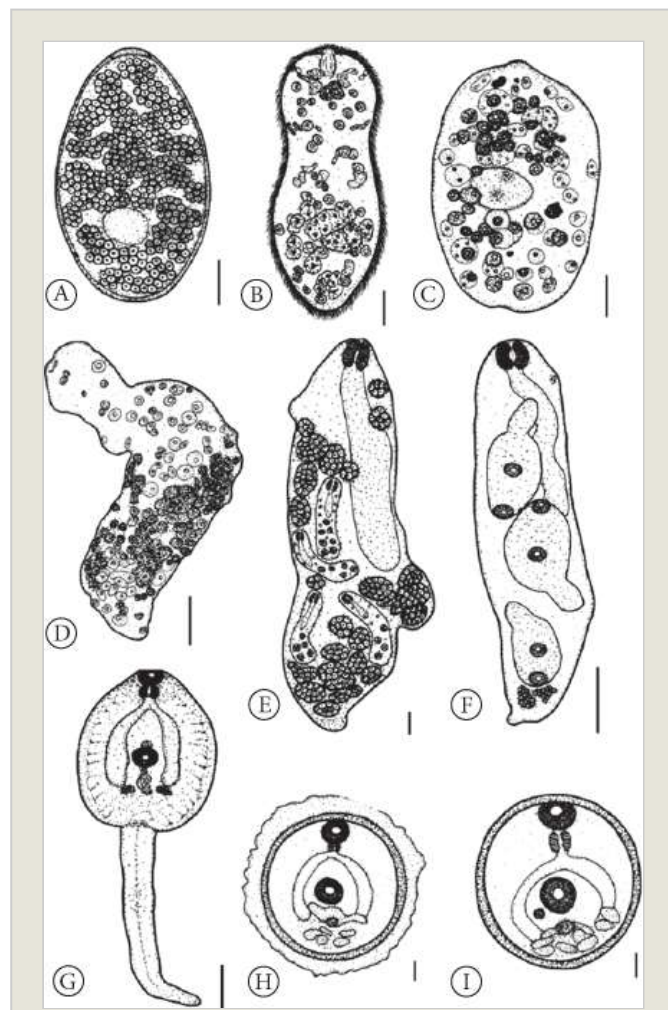
These kinds of considerations about species have led many philosophers of biology to reject 'biological essentialism'. To be precise, the form of essentialism being rejected is qualitative essentialism, or the view that a kind K has the essential property P if all and only members of K have P , where P is an intrinsic property or quality that is in some sense central to explaining what it means to be a K . Qualitative essentialism about biological kinds is recognized to be inconsistent with the fact that classification into biological kinds such as species tends to be based not on intrinsic properties (even if it is often informative about intrinsic properties), but on genealogical or historical-evolutionary relations (see Okasha 2002). In the present context, the important point to note is the following: if a species is a class defined by shared qualitative properties among its members, then the existence of significant qualitative variation within the species creates problems for the unity of the class. By contrast, if an organism's being part of a species is a matter of causal and genealogical relations, then there is no such problem. In principle, this ontology imposes no limits on the qualitative variation between different organisms in a species, either synchronically or diachronically.

Similar considerations motivate the categorial claim that biological individuals should be conceptualized as individual processes rather than as substances. As in the case of species, the reason has to do with qualitative variation: that is, qualitative variation between successive stages in the life of a biological system can make it difficult to specify an identical subject that passes through these stages. It is easier to simply drop the requirement that persistence is identity over time, and instead to construe it as a mereological relationship among the stages themselves. But this means discarding the category of substance as the paradigm for individuality in favour of the weaker and more flexible category of process, with its distinctive category features. I defend the view that processes lack the categorial features of numerical identity over time, persisting instead by having temporal parts, and they are individuated primarily by causal relations rather than by location. These are the features that make processes uniquely well suited for the categorial roles licensed by biological theory.

The argument can be made more concrete with an example. The class *Trematoda*, comprised of parasitic flatworms, is characterized by remarkably complex life cycles involving at least two hosts and several morphologically

distinct developmental stages. One genus of trematodes, *Fasciola*, is well researched due to its significant economic impact as a cause of disease in ruminants (and sometimes in humans). The life cycle of *Fasciola gigantica*, the giant liver fluke, begins with eggs laid in (p.80) mammalian gut excrement that hatch under aquatic conditions to release ciliated larvae (*miracidia*) (see Figure 4.1). The free-swimming larvae then penetrate an intermediary host (typically, snails from the family *Lymnaeidae*), where they develop through a number of larval stages. These are the oval sporocyst—a tightly packed ball of germinal cells (C–D in Figure 4.1); the cylindrical redia, which reproduces asexually (E–F in Figure 4.1); and the disc-shaped cercaria, with long swimming tails (G in Figure 4.1). Free-swimming cercariae then leave the intermediate host to encyst on vegetation that will be eaten by its definitive hosts, typically ruminants like sheep or cattle. When the encysted cercariae (i.e. the metacercariae) are ingested, they quickly excyst and take on the adult form of the liver fluke, eventually lodging themselves in the liver or in the bile duct, where they can increase in size by an order of magnitude over the next several weeks. Adult liver flukes reproduce sexually and lay eggs that find their way into the host’s excrement, thereby closing the life cycle (see Phalee et al. 2015).

(p.81) The development of *Fasciola gigantica* provides a vivid illustration of how different the stages of a life cycle can be. Other examples could be enlisted to highlight variability within ontogenies, as in complete metamorphosis. Intrinsic temporal variability in development is extensive and pervasive enough that attempts to consign the variation between stages to variation in accidental properties in favour of a core of identity would often be biologically unrealistic. This is not to say that no qualities remain the same over time. However, not just any stable qualitative property can provide a basis for diachronic identity. It should in some sense ground and/or explain other important features of the individual,



otherwise it could be that a peripheral quality that happens to be shared by all and only members of a kind defines its essence.

Given this explanatory requirement, an initially appealing idea is that diachronic identity in development can be grounded in the genotype—or, better, in the ‘extended genotype’ formed by gene regulatory networks (GRNs). In contemporary developmental biology, GRNs are frequently assumed to deterministically control development, and thus they could be interpreted as providing the individualized essences of developing organisms (see e.g. Davidson and Erwin 2006; Davidson 2010). The trouble with relying on GRNs for this role is that they often fail to meet the explanatory requirement. It is increasingly recognized that the mapping between GRN and phenotype can be highly non-linear, indeterministic, and degenerate owing to phenomena like developmental system drift (True and Haag 2001), structural robustness and canalization (Huang and Kauffman 2009), alternative splicing, post-translational modification, intrinsically disordered protein domains, and gene expression noise (Niklas et al. 2015). GRNs are no doubt crucial for understanding and explaining developmental processes, but not so far as to define a qualitative essence for a developing organism. And, if this is true for GRNs, it is all the more so for other candidate qualitative properties. The radical but effective solution in this situation is to discard the very requirement for a qualitative essence or diachronic identity criterion and take the developmental process as a whole to be ontologically primary (see chapter 11 in this volume).

This idea draws further support from evolutionary perspectives on life cycle variation. The descriptive study of life cycles has, in recent decades, increasingly come under the purview of life history theory, which uses optimality principles to explain the variation in adaptive traits at different stages of individual lifetimes (see Stearns 1992; Roff 1992; Flatt and Heyland 2011). Principal life history traits include size at birth, growth pattern, age and size at maturity, number, size, and sex ratio of offspring, age- and size-specific reproductive investments and mortality schedules, and longevity (Stearns 1992). These traits often constitute the major fitness components of an individual and are typically constrained by complex trade-offs with one another that demand significant intra-lifetime variation. Applying this framework leads to the important insight that life histories have a more fundamental status for evolution than organisms per se: given that fitness integrates over the entire reproductive performance of

Figure 4.1 Variation in the life cycle stages of *F. gigantica*: (A) egg, (B) miracidium, (C) young sporocyst, (D) mature sporocyst, (E) mother redia, (F) daughter redia, (G) cercaria, (H) encapsulated metacercaria, and (I) metacercaria. Scale bars (A–D) = 0.03 mm; (E–G) = 0.1 mm; (H–I) = 0.05 mm. Reprinted from Phalee et al. 2015, under a creative commons license.

a lifetime, selection acts to maximize the fitness of a life history as a whole (Flatt and Heyland 2011; see also Fusco 2001).

A similar kind of intrinsic temporal variation that is found in the life histories of multicellular organisms and in the evolution of species is also found in metabolic **(p.82)** processes. Recent research is increasingly highlighting the biological importance of circadian and ultradian variation in cells (see O'Neill and Feeney 2014). Virtually all important cellular events are parts of non-overlapping cycles involving intrinsic variation. For example, the primary metabolism of cells involves continuous oscillation between the chemically incompatible oxidative and reductive phases. It is not as though the contradictory properties instantiated by these stages can be reinterpreted as 'accidental' features, as this kind of variation lies at the heart of what is happening in cellular metabolism. Such variation creates serious strain for the conception of persistence as identity over time. To quote a review of the literature on circadian variation in hepatocytes (i.e. liver cells), this phenomenon: 'leaves one with the overwhelming impression that the humble hepatocyte is simply not the same cell between day and night' (ibid., 2971). Perhaps one should say that, indeed, it is not the same cell, and that the 'cells' are successive stages of an ongoing process.

These examples of intrinsic qualitative variation are relevant to ontology in the following way: the more qualitative variation there is between successive states of a persisting entity, the more difficult it will be to provide an ontological explanation of persistence in terms of qualitative identity or resemblance. This is what is required, however, for the enduring-substance conception of persistence, as I will show in section 4. But the problem is avoidable: without an identical subject that passes through each stage, one can interpret the stages as temporal parts of an extended process. Of course, stages and processes must also have identifying features; but, as we will see, without the requirement of numerical identity through time, defining these features can be much less demanding.

4. Criteria of Identity and the Individuation of Processes

It is sometimes thought that any category or kind *K* that we can coherently talk about—for example, the category of processes—must be associated with a *criterion of identity* for its instances, on the intuition that otherwise *K* is not theoretically well defined and cannot be actually applied. Some have even considered the absence of a criterion of identity for *Ks* to license the inference that there are no *Ks*. Quine, for instance, made an inference of this type from the lack of specifiable criteria of identity for intensions (see Horsten 2010: 412). Criteria of identity also appear in one popular view according to which ontological categories are only distinct if they are associated with distinct criteria of identity (Thomasson 2007; Lowe 2006). These considerations seem to

press the conclusion that a process-ontological framework must be able to provide a distinctive criterion of identity for processes.

A criterion of identity is a rule specifying the conditions under which items that belong to the same kind are identical. The two most common logical forms for criteria of identity are the following:

$$(I) \forall x \forall y \in K : x = y \leftrightarrow R(x, y)$$

$$(II) \forall x \forall y \in D : f(x) = f(y) \leftrightarrow R(x, y)$$

(p.83) A ‘one-level’ criterion (I) states that, for objects x and y of kind K , x and y are identical iff they stand in relation R . The paradigmatic example here is the axiom of extensionality as a criterion of identity for sets, according to which sets x and y are identical iff they have the same members (R). For a ‘two-level’ criterion (II), the right-hand side of the equation is the same as before, but the identity relation is between functions of objects $f(x)$ and $f(y)$, where x and y belong to the same domain D over which functions can be defined to constitute a kind $f(D)$ (Horsten 2010: 414). In Frege’s well-known example of a two-level criterion, the criterion of identity for the direction of lines $f(x)$ is given by the relation of parallelism (R).

A candidate criterion of identity is generally supposed to meet a few requirements: (a) R must be an equivalence relation; (b) it must be informative, in the sense of excluding at least some interpretations of the non-logical vocabulary on the right-hand side, and thus cannot be a merely logical truth like Leibniz’s Law (hereafter LL); (c) the criterion cannot admit of counterexamples; and, more controversially, (d) it cannot be circular or ‘impredicative’ (see *ibid.*). Because (II) requires defining a function over a domain of objects, it may be restricted to special classes of singular terms formed by means of functional expressions like ‘the direction of’ (Lowe 1989: 4). Criteria of identity for processes, if there are any to be found, should accordingly be one-level. Many putative one-level criteria turn out to be circular, however, and whether this afflicts the criteria for processes remains to be seen.

Before proposing a criterion of identity for processes, it will be instructive to consider first an example of (I) that is thought to be viciously circular: Davidson’s criterion of identity for events. According to Davidson’s criterion, events x and y are identical iff they have the same causes and effects (Davidson 1970: 306). The trouble arises when we recognize that causes and effects are themselves events, and thus we would need a criterion of identity for these cause events and effect events in order for events x and y to be identical, and so on for their causes and effects. Davidson’s criterion can therefore individuate events only if events are already individuated.

Seeking to avoid the impredicativity of defining R for events in terms presupposing event identity, Quine (1985) proposed that events are identical iff they occupy the same spatio-temporal region. This criterion successfully escapes circularity, since it is not based on a conception of event identity but rather of region identity. Underlying this difference with Davidson is a conception of events not as nodes in the causal nexus but as material contents of regions of space-time. However, Davidson (1985) raised a key counterexample to Quine's criterion. Imagine that a ball is simultaneously rotating and heating up. On the Quinean view, the ball's rotating and its heating up are the same event, because they occupy the same spatio-temporal region. If the ball's heating up causes the surrounding air to heat up, then the undesirable consequence follows that the ball's rotating is also what causes the surrounding air to heat up. Davidson's criterion, by contrast, can distinguish between the rotating and the heating up, but only if other events such as the heating up of the surrounding air are already individuated.

How does the matter stand with processes, then? Although events and processes may be distinguished in different ways (see Simons 2003; Steward 2013), they are relevantly similar in that both are extended in time and intimately bound up with causal relations. If processes are to be individuated causally in some sense, I take the **(p.84)** above counterexample to show that sameness of spatio-temporal region alone will not be suitable as a criterion of identity. Something more, as in Davidson's criterion, is needed—but without the same worrisome circularity.

I propose that the right approach to understanding biological processes is to be found in the *causal cohesion* account of individuation developed in a series of papers by Collier and colleagues (Collier and Muller 1998; Collier 2003, 2004). The cohesion account is based on dynamical systems theory and, though not intended specifically for events or processes, it extends over dynamical entities generally—in other words concrete entities that change, that are subject to forces, that are composed of physical parts at some level, and that can be described in terms of successive states. An entity is *cohesive* in the most general sense when it is demarcated by an interaction gradient—that is, when the causal interactions among its parts are stronger than the causal interactions between these parts and their environment, which grants it stability against perturbations (see Collier 2004). The probabilistic perturbation conditions under which a cohesive entity remains stable define its *cohesion profile* (ibid.). 'Stability' in this context refers to the recurrence of a *cohesion regime*, or to the specific interaction structure among parts that constitutes them as a unit. As an example, a Bénard convection cell is a cohesive entity because the macroscopic coordinated interaction among its microscopic parts is stronger than the interactions of these same parts with their environment. The cohesion profile of a convection cell includes its stability against a certain range of temperature changes, but not against perturbations like vigorous stirring. And we say that a

Bénard cell is stable due to the recurrence of physical convection—as opposed to turbulence—as its cohesion regime.

Cohesion can take different forms for different types of causal interactions at different scales, and can obtain due to first-order or higher-order dynamic properties. A rock is a cohesive individual, and it is individuated by the strong molecular bonds its parts have with one another but not with the environment. The cohesion of living cells is more complex and dynamic and of a higher order: it occurs by means of the recursive organization of chemical reactions whereby the material constraints on the dynamics of these cells (e.g. membranes, enzymes) are continually regenerated by those dynamics (Mossio and Moreno 2010; see also chapter 10 here). Higher-level and spatially diffuse systems can also be cohesive, for example a biological population, where the relevant interactions are primarily reproductive. According to Mayr's (1942) biological species concept, for example, a population is individuated by the reproductive interactions that are stronger among its parts than they are with parts of other populations. Even flocks of birds and schools of fish are weakly cohesive systems, in virtue of the sensorimotor feedback mechanisms that actively maintain a certain distance between the organisms. A cohesive individual may be considered 'robust' to the extent that it retains stability against a greater number of independent perturbations, and in this sense a single bird will be a more robust cohesive individual than the flock of birds it is part of.¹

(p.85) Cohesion is a functional property describing the condition under which an arbitrarily selected system is a genuine dynamical individual. Being a functional property, cohesion must be 'filled in' with the relevant interaction type for a given system. When this is done, and when the interactions of the relevant type meet the cohesion condition, we get access to a dynamical explanation grounding the *sortal* for the individual in question. Sortals are terms for sorts or kinds bearing determinate individuation criteria, which allow one to single out individuals of a kind as objects of unambiguous reference. The sortal 'cell', for example, is normally determinate enough to permit counting how many cells there are in a given region, or discriminating where one cell ends and another begins. It is only due to the cohesive interactions of metabolic processes, however, that there are individual cells to be singled out at all. Specifying the cohesion conditions for cells provides a causal explanation of the individuality of cells, and this can also be done for the other dynamical systems studied in biology.

On the basis of this conception of cohesion, the following criterion of identity for dynamical entities such as processes can be put forward: processes are identical iff they have all of the same cohesive properties, including cohesion profile and cohesion regime, and they occupy the same spatio-temporal region. 'Cohesive

properties' are to be understood as the dynamical properties a process has that make it cohesive.

How does the cohesion account fare with respect to the requirements on criteria of identity? It satisfies (a), given that sameness of cohesive properties and of region (R) are equivalence relations. The criterion is also informative, and thus satisfies (b); despite appearances, it is not merely a reformulation of LL, because any dynamical entity will display both cohesive properties and properties irrelevant to its cohesion (Collier 2003: 106). As for (c), which concerns counterexamples, a criterion of identity based purely on sameness of cohesive properties would face the troublesome counterexample that two spatio-temporally distinct individuals might instantiate exactly the same cohesive properties. The conjunction of cohesive properties and spatio-temporal regions disposes of this as well as of any counterexamples of spatio-temporally coincident but causally distinct processes.

Finally, does the cohesion criterion satisfy (d)—is it circular or impredicative? Arguably, it is not viciously circular like Davidson's criterion of identity; for, whereas Davidson defines R for events in terms of events, here R for processes is defined in terms of cohesive properties and regions rather than processes. However, the general definition of cohesion appears to be formally impredicative. When a cohesive individual is defined as one in which the interactions among *its* parts are stronger than the interactions between these parts and the environment, the definiendum appears in the definiens. Impredicativity could be avoided if one could individuate a cohesive entity solely by examining the interaction structure of a set of putative parts without having to decide in advance which parts are parts of the entity. In many cases, though, it will be necessary to rely on hypothetical demarcations as well as on top-down functional criteria to determine the relevant interaction types for assessing cohesion in specific cases. In determining where one ecosystem ends and another begins, for example, it is necessary to have some idea of where to look as well as of what kinds of interactions to look for (nutrient cycling, trophic exchanges, etc.). Starting from a hypothetical ecosystem, one can decompose the system to examine **(p.86)** the interaction structure of a wider set of parts, then use that information to recompose and potentially revise the initial demarcations. There is a sense in which this procedure is circular but, unlike Davidson's criterion, this circularity does not make individuation epistemically inoperable. The fact of starting from some initial system of interest would not seem to pose a problem so long as the revision criteria allow one to eventually converge on the right cohesive individuals, even if the initial system is arbitrary.

One consequence of adopting the cohesion account for processes is that the notion of individuality becomes weaker and more permissive than the individuality associated with substances. Traditionally, substances are characterized by the categorial features of particularity, countability,

concreteness, independence, unity, and endurance—among other features (see Seibt 2010 as well as chapter 6 here). Cohesive individuals, however, need not have the feature of particularity, that is, a necessarily *unique* spatio-temporal location; examples would be processes like heat flow, air flow, or chemical reaction networks like the Krebs cycle, which can spatially overlap with other biochemical processes in cells. The parts of a cohesive individual can also be spatially scattered rather than connected—as are for example flocks of birds, populations, or some ecosystems. The ‘weak individuality’ of cohesive systems may be an advantage in cases where biological models represent causal interactions between non-conventional individuals, such as Lotka-Volterra population interactions. In such cases, weak individuality fulfils the categorial roles for biological individuality better than the strong notion of substance does.

This conception of processes as concrete independent individuals evidently doesn’t track exactly with English usage in the case of the word ‘process’. This noun is, in fact, ambiguous: sometimes it denotes a concrete occurrence and sometimes an instantiable pattern. The phrase ‘the process of evolution’ can denote the entire historical chain of developments from the last universal common ancestor to present-day life on Earth, which is a concrete and non-instantiable occurrence. But it can also denote a pattern, or a regular distribution in the properties of some individuals over time, which is instantiable at different times and places in the universe. Concrete processes can be what instantiates these patterns, but the latter must be instantiated in order to exist, because they are abstract and dependent. The focus of process ontology, in my view, ought to be on the development of the category of concrete independent processes rather than on process patterns, as only the former have the right categorial features to replace the category of individual substances.

5. Process Persistence: Identity versus Composition

The most salient categorial difference between substances and processes concerns their persistence in time: substances persist by being numerically identical through time, whereas processes persist by having temporal parts at different times. As I have argued, this is also the primary difference that gives a process-based representation of biological systems greater explanatory power in biological contexts, as it has no problem handling phenomena of intrinsic temporal variation (on this issue, see chapter 13). Before concluding in favour of the process view, however, it is necessary **(p.87)** to examine in greater depth why exactly the substance view is committed to a problematic form of essentialism and whether the alternative model of persistence is actually coherent.

According to the account of ontological explanation outlined in section 2, evaluating different models of persistence as to their explanatory power will

require clarifying the categorial roles for persistence. These can be expressed in ordinary statements about change (A) and reidentification (B) (see Seibt 2008):

- (A) This liver fluke was ciliated, but now it is not.
- (B) This is the same liver fluke as the one you saw yesterday.

More specific categorial roles can be added for specific domains, for example roles for distinguishing biological parents and offspring. But a model of persistence for *any* class of concrete entities must fulfil categorial roles for both change and reidentification over time, thereby explaining how statements like (A) and (B) can both be true. As might be expected, substance ontology tends to have greater difficulty with (A), whereas process ontology tends to have greater difficulty with (B).

5.1. The endurance of substances

Putative biological substances—organisms, organs, cells, and so on—are said to persist by enduring or being ‘wholly present’ whenever they exist. The easiest way to clarify the notion of being wholly present is to define it negatively, so that it consists in the denial that objects thought to be substances have temporal parts. This requires defining a minimal notion of temporal parthood (TP) at a time (see Sider 1997: 205):

TP: x is a temporal part of y at $t_i =_{df}$ (i) x exists at t_i and only at t_i , (ii) x is part of y at t_i , and (iii) x overlaps at t_i with everything that is part of y at t_i .

I leave it open whether t_i is an instant or an extended interval of time. Temporal parts or stages should be conceived of as the smallest units of difference over time for a given process, relative to a given granularity or resolution. Say y is a whole life history and x is a certain stage in the life history, such as the stage of reaching maturity. The core idea of the above definition is that this stage is temporally located at a certain time, and that everything of the life history that exists at that time is just stage x .

When enduring things are said to be wholly present (WP) whenever they exist, this means that they lack temporal parts.

WP: y is wholly present at $t_i =_{df}$ (i) y exists at t_i , (ii) there is no x such that x is a proper temporal part (TP) of y at t_i .²

(p.88) For an organism y , what exists of y at any instant when y exists is y itself, and not just a part of y . If y persists or exists at multiple times $t_1, t_2 \dots t_n$, this means that y at t_1 must be *identical* with y at t_2 and with y at t_n . This is the sense in which endurance is identity through time.

The endurantist view quickly encounters the problem of change, however, as expressed in (A) above. If a liver fluke is ciliated at t_1 and then not ciliated at t_2 , the fluke at t_1 cannot be identical with the fluke at t_2 . Initially one might try to

resolve this tension by distinguishing between qualitative identity and numerical identity. A statement about change like (A) would then only pertain to the qualities of the fluke—say, its having cilia or not—while its numerical identity would remain unaffected by change. Similarly, the reidentification expressed in (B) would only pertain to the numerical identity of the fluke, and not to its qualitative features. This distinction between qualitative and numerical identity becomes untenable, however, once they are logically connected by means of LL (see Seibt 2008: 136), which states that there is no numerical identity without qualitative identity.

$$\text{LL: } x = y \leftrightarrow \forall F (Fx \leftrightarrow Fy)^3$$

In effect, if change is qualitative difference over time, then an entity cannot change and remain numerically identical. Endurance would be impossible.

The classical strategy for dealing with this problem is to restrict the scope of LL so that it only quantifies over *essential* qualitative properties. An enduring thing could then change in its accidental qualitative properties while remaining numerically identical over time; but, if it changed in its essential qualitative properties, it would become a numerically distinct individual. This is the sense in which endurantism must be tied to some form of essentialism, because otherwise persistence as numerical identity despite change would not be possible.⁴

As for what the essential properties are, these are often taken to be determined by the sortal that the entity falls under, which specifies identity conditions for the kind of entity in question (Lowe 2009; Wiggins 2001). Substances are of course not the only items that are classified into kinds. There are also kinds of events and processes, and individual events and processes will have essential properties to the extent that they are individuals of certain kinds. The important difference, however, is that substances must fall under sortals that specify synchronic *and* diachronic identity conditions. At every time at which a substance exists, there must be an intrinsic property or set of intrinsic properties whose qualitative sameness grounds its numerical identity through time. Processes, by contrast, can belong to kinds in virtue of essential *relational* properties, or in virtue of intrinsic properties that are instantiated by **(p.89)** *different* temporal parts. Such is the case, for example, with the process kind ‘the life history of *Fasciola gigantica*’.

A different endurantist solution to the problem of change is to hold that all properties instantiated by a substance are time-indexed. It may be contradictory for a substance to be both ciliated and not ciliated simpliciter, but not for it to be both ciliated-at- t_1 and not-ciliated-at- t_2 . The problem here is not just that all intrinsic properties become relations to times, as Lewis (1986) pointed out. Given that the continuant maintains its numerical identity over time, it now has

all of its time-indexed properties *at all times*. At t_1 , the liver fluke has the properties of being ciliated-at- t_1 and being not-ciliated-at- t_2 . It has these same properties at t_2 . Arguably, this fails to meet the explanatory requirements for change as expressed in (A), which says simply that the individual's properties at t_1 are different from its properties at t_2 .

It is worth noting that the problem of change does not arise for the temporal parts view, because the latter does not conceptualize persistence as identity over time—numerical or qualitative. Hence there is no problem in saying that a stage x_1 at t_1 is ciliated and another stage x_2 at t_2 is not ciliated, and that stages have their intrinsic properties simpliciter.

There are several other problems with endurantism that may be relevant to ontological issues in biology, including the need to introduce artificial discontinuities when a continuant begins or ceases to exist. On closer inspection and viewed with a finer grain, discontinuities such as birth, death, or speciation are based on continuous developments. Similarly, phenomena of fusion, fission, or overlap are more easily handled through the concept of temporal parts. Just as two distinct substances can share spatial parts, processes can share temporal parts without this impinging upon their individuality. The capacity of processes to easily accommodate continuity and overlap is an advantage in biology, where these phenomena are common. Reproductive processes, for example, are thought to involve the offspring and the parent's sharing (some) material parts, and temporal parts of those material parts (see Griesemer 2000).

The strongest argument against endurantism as a general ontological thesis is often thought to be the argument from the relativity of inertial frames in special relativity, which implies that there is no privileged present to ground the notion of being wholly present. In biological contexts, however, the strongest argument targets the endurantist commitment to qualitative essentialism. To be sure, in many cases it will be possible to identify non-trivial properties that retain qualitative sameness over the course of a dynamical trajectory, which can even serve to ground the conception of a substance that traverses the trajectory. But, because there will also be cases where this procedure becomes strained, it should not be built in as a requirement on biological ontology.

5.2. The perdurance of processes

The core idea of the alternative model—perdurantism—is to deny that persistence is a matter of the numerical identity of entities that exist at different times, and to claim instead that it is a special mereological relationship.⁵ From this perspective, **(p.90)** statements like (A) are made true by the fact that the ciliated and the non-ciliated organism are different temporal parts of a temporal whole, which is the liver fluke's life history, while statements like (B) are made true by the fact that the parts are parts of the same whole. The main attraction of this view in the present context is that there is virtually no restriction on the

variability of properties among the temporal parts themselves, except that they must be able to stand in the appropriate composition relationship.

Many of the objections to perdurantism simply express incredulity that it can adequately capture our habitual thinking about change or transtemporal sameness (e.g. Chisholm 1976; Wiggins 2012), but such objections have little force on the model of ontological explanation from section 2. The main objection that should be addressed concerns the capacity of processes to instantiate the properties that substances can instantiate. For the central strategy of perdurantism is to reject the endurantist idea that statements (A) and (B) refer to the same entities. Instead, change statements refer to temporal parts, whereas reidentification statements refer to temporal wholes (see Seibt 2008: 159). However, it would seem that many of the predications we make of items thought to be substances express properties that cannot be exemplified by either instantaneous stages or temporal wholes.

For example, an organism eats, but one of its instantaneous stages cannot eat. Rather, the stage is succeeded by another stage that has different eating properties. Since eating takes some time to occur, it can only be a property of a stage if the stage is temporally extended. However, if a stage is temporally extended, then arguably it must persist through some change. Then either the stage persists through change by perduring, in which case the same problem is repeated for *its* stages, or it endures, and the perdurance thesis fails to obtain after all (see Seibt 2008: 143). Similarly, the entire life history of an organism doesn't have properties like eating or moving, but only properties like occupying a certain spatio-temporal region.

A perdurantist could respond that a time-extended property instance such as moving, eating, digesting, and so on is itself a process or an activity and need not be exemplified by *a* stage but by several stages that, together, have the suitable interrelations. The above argument begs the question against the perdurance view by assuming that these processes are not analysable into smaller units of difference, since this is just what persistence is, on the perdurance view. But the critic might respond that this does not adequately explain persistence. Specifically, it captures the aspect of difference but not the aspect of sameness. The process of eating is internally differentiated into stages, but what makes them stages of the same **(p.91)** process? A closer examination of the composition relation for stages is required for resolving this difficulty.

It will be noticed that the analogous question for enduring substances asks for a criterion of identity—a *diachronic* criterion of identity—that takes the following form (see Merricks 1998):

$$(III) \forall x \forall y \forall t : xatt_1 = yatt_2 \leftrightarrow R(x, y, t_1, t_2)$$

Because process persistence is a mereological relation rather than identity relation, however, it takes a different logical form, where x_n are temporal parts, y is a temporal whole and ' $<$ ' is the parthood relation:

$$(IV) \forall x \forall y : x_n < y \leftrightarrow R(x_n, y)$$

6

The question is, then, under what conditions (R) are temporal parts (x_n) parts of the same temporal whole (y)? Certain answers to this question would be *prima facie* excluded in biological contexts—for instance, that composition occurs under all conditions (mereological universalism) or under no conditions (mereological nihilism). When evolutionary biologists count the number of offspring in order to measure a parent's reproductive fitness, they do not count later stages in the life history of the parent as another offspring. An ontology ought to be able to differentiate between the persistence of an individual and the reproduction of new individuals, and it is not clear how mereological universalism or nihilism about temporal parts could do so in a principled way.

Composition can be plausibly restricted for biological individuals by specifying R in (IV) as a type of *causal continuity*, sometimes also called 'genidentity' (Lewin 1922; Hull 1978; Guay and Pradeu 2015; see also chapters 2, 5, 7, and 11 here). More precisely: the x_n compose y if y is the sum of causally continuous stages x_n . On this view, two temporally separated stages in the life cycle of *Fascicola gigantica* are parts of the same life cycle not because they resemble each other, but because they are linked in a continuous causal chain. Of course, allowing that any amount of causal continuity satisfies R would make R overly permissive, since a stage tends to be causally continuous with more than what should be included in a biological individual. The life cycle of deciduous trees includes the loss of leaves, for example. Let x_1 be a tree stage with leaves at t_1 , x_2 be the tree stage without leaves at t_2 , and z_2 be the fallen leaves at t_2 . Why is x_1 continuous with x_2 rather than with z_2 ? If dead leaves don't count as cohesive biological individuals, the same question can be posed with z_2 as offspring. In response, one can distinguish between partial and total continuity: the continuity between x_1 and z_1 is partial—namely, it is only the leaves that are retained—whereas that between x_1 and x_2 is near-total, as it is the whole tree (minus its leaves) that is retained. In different contexts of inquiry and for different kinds of entities, different degrees of partial continuity will dictate whether a given x_i is **(p.92)** considered a new individual or a continuation of the same individual. In general, however, the causal continuity relation R can be specified as *relatively greater partial continuity* between stages whenever there are multiple stages partially continuous with the same earlier stage.

This interpretation of (IV), where R is relatively greater partial continuity and the x_n are cohesive individual stages, is capable of explaining the truth of (A) and

(B) while also distinguishing between parent and offspring processes in a biologically satisfactory manner. (A) is true because the ciliated fluke and the non-ciliated fluke are qualitatively different cohesive stages (x_n), and (B) is true because they are related through causal continuity (R). When the liver fluke lays eggs in its definitive host, the eggs are stages of a distinct individual process because they have less partial continuity with earlier stages of the parent than the later parent stages do.

6. Conclusions

Process ontologies for the life sciences have continued to attract theorists for a variety of biological reasons. I have argued that, if this sort of ontology is empirically well motivated (where motivation is a matter of ontological explanatory power), then it should be an ontology in which the categorial roles for enduring substances are realized by perduring cohesive processes. This shift has the advantage of dropping the substance ontologist's commitment to qualitative essentialism and the too strong equation of individuality with particularity without any serious sacrifice of explanatory power.

The implications of adopting this sort of framework, given its high level of abstraction, are likely to be felt more in philosophical reflections on the life sciences than in the life sciences themselves. However, to the extent that scientific research is guided by theoretical and philosophical presuppositions, the processual perspective might help to overcome some unnecessary ideological obstacles to theoretical progress; for example, the notion that causation can only occur between particulars, or that informative kind classification requires qualitative essentialism, or that diachronic criteria of identity are necessary for distinguishing between biological individuals.

One interesting consequence of the idea of ontological explanation for scientific domains from section 2 is that, as long as a domain is still developing, the domain ontology cannot make a claim to completeness or finality. A process ontology for biology should therefore be viewed as a provisional categorial interpretation of the biological domain that is susceptible to revision as the science changes. In attempting to get clear on what biological processes are, however, at least we will have provided tools for revision.

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Notes:

(¹) For more on the notion of robustness as a criterion for (belief in) the reality of an entity, see Wimsatt (2007: 43 ff.) and Eronen (2015).

(²) Note that, on this definition, if *y* is instantaneous, then there can be an *x* that is an *improper* temporal part of *y* at t_1 —i.e., *x* is the *only* temporal part of *y*. In this case we get the seemingly strange result that, if *y* is instantaneous, it can both be wholly present and have a temporal part. As a consequence, the statements ‘*y* endures’ and ‘*y* perdures’ only become distinct if *y* is non-instantaneous. While this may pose a problem for exdurance views (Sider 1996, 1997, 2001), it is not a problem for other views of persistence in which, if *y* is instantaneous, then by definition it does not persist.

(³) The principle of the identity of indiscernibles and the converse principle of the indiscernibility of identicals are here combined.

(⁴) It is possible for a 'continuant' to have a relational rather than qualitative essence, whereas this wouldn't be possible for substances, as long as they have the categorial feature of independence. However, because continuants lack other categorial features besides enduring, they do not comprise a robust ontological category, and so the ontological problems with the category of substance cannot be avoided simply by switching to the more non-committal notion of continuants.

(⁵) Perdurantism theories have often been motivated by the development of the theory of relativity, and in particular by the unified concept of space-time, as famously described by Minkowski. Accordingly, many formulations of perdurantism rely on the idea that, since space and time are fundamentally unified in relativity theory, so temporal parts must be fundamentally similar to spatial parts. But this introduces a number of unnecessary metaphysical commitments about time into the ontology of perdurance, such as eternalism and the B-theory of time. A theory of temporal parts can be explanatorily adequate to (A) and (B) without invoking a constitutive analogy with spatial parts. The reason why a constitutive (rather than a heuristic) reading of the analogy between spatial and temporal parts implies eternalism and/or the B-theory of time is that spatial parts all exist, which implies that future (and past) temporal parts should also exist (i.e. eternalism). The analogy also causes problems when one imagines temporal parts to be discontinuous, as spatial parts are sometimes taken to be. Neither of these associations is necessary, as can be appreciated by examining ordinary talk about occurrents like events and processes—talk that involves no apparent commitments to eternalism or discontinuity.

(⁶) Note that one can differentiate one-level and two-level principles of composition, where the former characterize the composition relation in terms of relations between parts and wholes, and the latter characterize it in terms of relations between other items (e.g. regions, constituting stuffs) that are functionally related to parts and wholes (see Hawley 2006). Here as before, I assume that one-level principles are more germane to the temporal composition of biological processes.

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