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ORIGINAL RESEARCH

Time Scales and Levels of Organization

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Abstract The concept of levels of organization, despite its widespread scientific currency, has recently been criticized by a number of philosophers of science. This paper diagnoses the main source of problems facing theories of levels. On this basis, the problems with the usual criteria for distinguishing levels are evaluated: compositional relations, organizational types, and spatial scales. Drawing on some work on hierarchies in ecology, I argue in favor of an alternative conception of levels defined by the criterion of rates or time scales of processes.

1 Introduction

The idea that nature is structured hierarchically or according to different levels of organization is an important ontological principle in the sciences, especially in the life sciences. William Wimsatt expresses a commonly shared sentiment when he writes: "Levels of organization are a deep, non-arbitrary, and extremely important feature of the ontological architecture of the natural world" (2007, 203). Hierarchy concepts have also taken on an increasingly central role for a variety of problems in philosophy of science, featuring prominently, for example, in debates about reductionism and emergence, downward causation, units of selection and multilevel selection, and biological individuality.

Recently, however, a number of philosophers have expressed skepticism about hierarchical representations of nature, and particularly about the classical levels of organization concept (Craver and Bechtel 2007; Bechtel 2008; Ladyman and Ross 2007; Rueger and McGivern 2010; Potochnik and McGill 2012; Eronen

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2013, 2015). It is argued that the distinctions between levels cannot be made consistent, or that the aims of hierarchy theory can be better satisfied with concepts other than levels, such as material composition and scale (Eronen 2013; Potochnik and McGill 2012). In general, the suspicion is that nature may be too "messy" to admit of a global hierarchical ordering into levels.

This paper aims to specifically re-assess the idea of *causal* levels of organization in light of the criticisms addressed to the concept of levels, and to evaluate whether it might be usefully reformulated in some way. After a preliminary discussion of the aims and requirements for a causal hierarchy theory, I evaluate the problems that have motivated skepticism about levels by examining the usual criteria for distinguishing levels: namely, compositional relations, organizational types, and spatial scales. Drawing from some work on hierarchies in ecology, I argue for a particular reconfiguration of levels of organization in terms of the criterion of rates or time scales of processes.

2 Levels and the Aim of Hierarchy Theory

For all its familiarity and currency, the concept of levels is rarely explicitly accounted for. On closer inspection, there are many different conceptions of what levels are and what their theoretical role is that should be distinguished.

One kind of levels is levels of organization, which is the sense of levels that will be discussed here. But there are also levels of description, levels of explanation, levels of abstraction, levels of complexity, levels of generality, levels of control or regulation, and more. Most commonly, though, levels are thought of in two ways. In the classical levels of organization concept often used in the sciences, levels are construed as levels of reality ordered by compositional or part-whole relations. Entities at one level (l_i) are parts of entities at the next higher level (l_{i+1}), which in turn are parts of entities at the next higher level (l_{i+2}), and higher-level entities are ontologically dependent on lower-level entities. This gives us the classical levels of organization hierarchy: at the lowest level would be elementary particles, followed by the atomic level, the molecular level, the macromolecular level, the cellular level, the organismic level, the population level, the community level, the ecosystem level, the biosphere level, or some similar variation.[1] Alternatively, levels are thought of in terms of relationships between the sciences. There is a familiar hierarchy of sciences ordered by levels of generality: physics, chemistry, biology, psychology, sociology and economics. This is the hierarchy that is usually behind discussions of explanatory or theory reduction (e.g., Oppenheim and Putnam 1958; Nagel 1961), whereas the former is usually behind discussions of ontological reduction. Obviously these two hierarchies are closely related, but they do not map neatly onto one another and so they should be carefully distinguished. It is the levels

[1] In case there is any doubt that there is such a classical levels of organization concept, one can consult virtually any standard textbook in biology or ecology. See, for instance, Campbell et al. (2011, 3 ff.), Molles (2008, 2 ff.), or Starr et al. (2009, 4 ff.)

of organization hierarchy and not the hierarchy of the sciences that will be of primary concern here.[2]

Investigation of levels of organization as a distinct theme is a philosophical or metascientific project which, under the guidance of specific aims, issues in a theory or account of levels. It is particularly important to get clear on what these guiding aims are, because only then is it possible to ground the choice between rival accounts as well as to evaluate whether a general hierarchy theory is possible at all. There may be various aims of theories of levels, such as explicating what scientists mean by levels or setting up a general framework for reducing higher-level entities to lower-level entities. I will focus on what I take to be the primary *ontological* aim, which is to capture some deep aspect of the causal structure of nature. More precisely, the ontological aim is to provide a reliable guide to the structural segregation of causal interactions in the world, where the sciences determine the scope and content of these causal interactions. This aim is reflected in what most theories of levels attempt to do. In Wimsatt's extensive discussion of levels of organization, he writes:

> Ontologically, one could take the primary working matter of the world to be causal relationships, which are connected to one another in a variety of ways—and together make up patterns of causal networks…. Under some conditions, these networks are organized into larger patterns which comprise *levels of organization*. (2007, 200)

Craver and Bechtel (2007), in their account of levels of mechanisms, define the intralevel relation and interlevel relation in such a way that causal interactions do not occur between interlevel entities. Similarly, Salthe (1985) and Eldredge and Salthe (1984) stipulate that direct causation or dynamical interaction only occurs between intralevel entities, whereas interlevel entities can only relate via upward or downward *constraints*. Where these authors agree is that the critical factor for assessing whether levels are tracking with causal structure is the absence of direct causal interaction between interlevel entities. For two relata, being at the same level doesn't necessarily mean they will causally interact, nor does being at different levels mean that constraints will always be present, but being at different levels does mean that there should be no (or very little) direct causal interaction between them.

A causal interaction in the relevant sense should be understood quite broadly as a difference-making relationship such that X and Y causally interact iff an intervention on X changes Y and vice versa (see Woodward 2003). Of course, very many variables make some difference to one another, but not all will be significant. Moreover, some difference-making relationships are nondirect and are better described as constraints, e.g., when an enzyme catalyzes a chemical reaction. This is

[2] In discussions of levels of organization, it has become customary since Hull (1980) to differentiate biological entities as "interactors" or "replicators," with interactors forming an "ecological hierarchy" and replicators forming a "genealogical hierarchy" (see Eldredge and Salthe 1984; Salthe 1985). The notion of levels of organization to be treated here is concerned with causal interaction in general rather than replication in particular, thus it is more similar to the ecological hierarchy. Unlike in Hull's framework, however, it is not restricted to interactors conceived as units of selection—i.e. entities that interact with the environment "in such a way that replication is differential" (Hull 1980, 318).

contrasted with paradigmatic instances of direct causal interaction—e.g., one organism eating another, or molecular collisions. In a constraint relationship, the constraint asymmetrically influences the behavior of what it constrains by reducing its degrees of freedom in some specific way, but without being affected by the constrained dynamics. Constraints also tend to be greater in spatiotemporal scale than what they constrain (though not always for spatial scales, for example, with catalysis). These features of the constraint relation, namely, asymmetrical influence and scalar difference, underlie its close association with the concept of levels (Umerez and Mossio 2013). In the absence of constraint relationships, however, it seems that there can still be something like differences of level. An organism may be insulated from the overall dynamics of its population simply due to scalar differences and without there being distinctive constraint relationships between them, much in the same way that an individual molecule is insulated from the statistical macroscopic behavior of a gas. This may constitute useful causal information that should be embedded in an account of causal levels.

For the purposes of determining levels of causal structure, then, there are two conditions each sufficient for being at different levels: (1) the direct interaction is nonexistent or weak relative to the characteristic behaviors of the relata, and the relata are located in the same interactive context (i.e., they do not fail to interact simply due to being far away from one another); or (2) the interaction is one of constraint. Because condition (1) is the more general one, it is the primary condition of interest for a theory of causal levels. Herbert Simon sums up the situation nicely:

> Everything is connected, but some things are more connected than others. The world is a large matrix of interactions in which most of the entries are very close to zero, and in which, by ordering those entries according to their orders of magnitude, a distinct hierarchic structure can be discerned (1973, 23).

Alternatively, one might also plausibly characterize the ontological aim of theories of levels as discovering globally valid typological groupings of entities, or using levels to discover *natural kinds*. The classical biological levels of organization hierarchy yields natural kind-like classes of a particular type which I will refer to as "organizational types": namely, cells, organs, organisms, populations, communities, ecosystems, etc. If organizational types turn out to be natural kinds, then classifying an entity as belonging to a certain organizational type should allow us to make inferences about its properties and about the laws that govern its behavior. However, the aims of describing causal demarcations and of discovering natural kinds through hierarchy theory might not be jointly achievable, and may promote different criteria for distinguishing levels. In fact, this is what I will claim below in granting primacy to the aim of describing causal demarcations.

Given the specific aim and the kind of levels that will be discussed here, it still should be clarified what a "level" itself is supposed to be. The concept of levels is sometimes characterized—perhaps disparagingly—as a "metaphor" (Schaffer 2003, 500; Ladyman and Ross 2007, 54; although see Craver 2015). While this may be true as a matter of origins, there is nothing to prevent giving a more technical meaning to the concept. Levels are types of *classes*, and the entities that are situated at levels are members of these classes (Salthe 1985). Ontologically, members of level-classes are *individuals* (or types of individuals)—that is, concrete, countable, independent, and persistent units. A population is a concrete individual, whereas the population level is an abstract class having population-individuals as members. It is important to keep this fact in mind, because it is much easier to dismiss the concept of levels if one has already reified it in such a way that levels would have to be concrete entities "out there" in the world. Hierarchical classifications nevertheless refer to real divisions in the causal structure of the world, and different hierarchy constructs can be better or worse at capturing this structure. It is this structure that is real, and levels are a way of representing it.

There are two basic conditions under which a theory of levels will be unsuccessful at representing this structure, thereby failing to satisfy its main ontological aim. The first is that nature is too irregular, too complicated, or too messy to have something like a causal structure or to admit of any reliable classification. Alternatively, it could be that nature *is* regular, it does have some causal structure, and does admit of some reliable classification, but that this structure cannot be consistently rendered into the type of classes that levels represent. Levels are not classes that can be independently conformed to whatever regularities and types are in fact found in nature. Levels are classes ranked in an ordered series l_i, l_{i+1}, l_{i+2}, …, l_n. A level l_{i+1} is logically generated by applying a fixed operation on the preceding level l_i such that, for instance, l_i entities are "parts of" l_{i+1} entities or are "smaller than" l_{i+1} entities. This operation must be fixed—i.e., within the same hierarchy, it must be the same levels-criterion for each successive level—otherwise we are not dealing with *a* series or *a* hierarchy, and we are not talking about levels but about some other type of classification.

As we will see, this is where the whole problem lies. A levels-criterion is now required to be both causally adequate—i.e., describing the structural segregation of causal interactions—and consistent—i.e., the same for each successive level in the same hierarchy—but it is questionable whether such a criterion can be found. Given this situation, it is tempting to collapse these two requirements into one by making causal segregation itself the levels-criterion, as Potochnik and McGill (2012, 137) suggest. Unfortunately, this would be circular: since hierarchical causal segregation is what a theory of levels aims to describe, the levels-criterion must be something besides causal segregation. Otherwise, one would already have to know the relevant interaction structure in order to classify things into levels, and level-classifications wouldn't provide any additional causal information and wouldn't do any theoretical work. If no suitable criterion can be found, however, then the theory of levels will do no work anyway.

3 Universality and Discreteness of Levels

In light of their primary ontological task—namely, finding a levels-criterion that is both consistent and (causally) adequate—hierarchy theories will tend to run into a persistent problem. In general, for any hierarchy that manages to be consistent, it will always be possible to find counterexamples where interlevel entities directly causally interact, thereby undermining the hierarchy's division of levels and causal interactions. Against a size-scalar hierarchy, for example, in which entities only directly interact if they are of a similar size (to within a specified range of variation), one could point to black holes destroying whole nebulae, small amounts of toxic substances killing large animals, or various "butterfly effect" phenomena. Counterexamples to other hierarchy constructs are presented in Sect. 4 below.

It is not difficult to show how any hierarchy will fail to be both consistent and adequate as long as it is assumed that levels must be *universal* and *discrete*. Levels are universal iff everything that exists exists at some level in the same hierarchy. They are discrete iff membership in level-classes is disjoint, i.e., each entity belongs to only one level. Together these two requirements in principle ensure a global and unique distribution of things at levels. On closer inspection, however, there is no compelling reason to think that levels must necessarily be strictly universal and discrete. Potochnik and McGill claim that the traditional compositional levels of organization hierarchy "is often taken to involve stratification into discrete and universal levels of organization" (2012, 121); moreover, concerning levels of any kind, "the very formulation of the concept suggests universality" (2012, 133). It stands to be demonstrated, however, that this suggestion is really necessary to the concept of levels, and that the levels of organization idea cannot be suitably reformed. Levels can coherently lack strict universality and discreteness, I argue, and still have ontological significance—though they will tend to be more informative the more general and discrete they are.

Given the huge variety of systems and interactions described by current science, as well as the heterogeneity of different scientific disciplines and practices, it would be very surprising indeed if classification into a universal and discrete hierarchy were possible. As critics of the levels of organization concept have pointed out, a question like whether glaciers, elephants, enzymes, and computer chips are on the same or different levels is not well-defined (Bechtel 2008, 147; Craver 2007, 191; see Eronen 2013, 1044). But this is also not how the levels concept has typically been used by scientists. Even if the formulation of the concept suggests universality, the original motivations behind its introduction have been more restricted in scope. Hierarchy theory as a formal theory of levels largely grew out a cluster of theoretical frameworks around the middle of the twentieth century that developed in order to deal with problems of complexity, such as cybernetics, complexity science, and systems theory (see von Bertalanffy 1969). Hierarchical structure is particularly salient in complex organized systems: most paradigmatically biological systems, but also non-living dissipative structures, cybernetic machines, and social and economic systems.

The special connection between hierarchy and complexity was explored in Herbert Simon's classic papers, "The Architecture of Complexity" (1962) and "The Organization of Complex Systems" (1973), as well as in William Wimsatt's "Complexity and Organization" (1972) and "The Ontology of Complex Systems" (2007). Without going into too much detail, the basic idea is that hierarchical structure grants a degree of stability to complex systems without which they would not be able to persist over time. A system is complex in the relevant sense if the interactions among its parts are such that the system's behavior cannot be straightforwardly inferred from the properties of its parts (Simon 1962, 168). It occupies only a small region of its total physical phase space, and persists in "improbable" macrostates that are compatible with only a narrow range of microstates. This usually requires stabilizing mechanisms such as negative feedback loops, but stability is also greatly enhanced when interactions among parts in the system are compartmentalized into sub-systems. The greater the number and variety of component interactions in a system, the greater the likelihood that destabilizing fluctuations will propagate through it (see Ashby 1954). Hierarchical segregation is a way of preventing dynamical interaction between sub-systems of a system, thereby stabilizing the different "levels" of sub-systems and sub–sub-systems within a system. I return to this important connection between dynamic stability and hierarchical structure below in arguing for a time scale levels-criterion.

If hierarchical structure has this specific role to play in complex organized systems, then it should not be surprising that the concept of levels becomes strained when it is extended over any and every kind of system, such as black holes, computer chips, and glaciers. It is also not surprising to hear that the concept of levels might have no crucial role in fundamental physics that cannot be fulfilled by concepts of scale (see Ladyman and Ross 2007)—particularly spatial scale and force scale. This does not imply that the levels concept lacks ontological significance, but only that it lacks universal scope: levels are part of the ontology of complex systems (Wimsatt 2007). Hierarchy is not—and never was—a universal stratification of being, but rather a dynamical structure for complex systems. This restricted scope gives a very different picture of what hierarchies are supposed to be than the one that is assumed by many of the philosophical critics of levels of organization. Rather than a universal and discrete division of causal interactions or types, to the contrary, it is both more plausible and closer to the scientific use of the concept to think that a hierarchy offers *reliable generalizations* about the structure of causal interactions in complex systems—not universally for any and every system, and not without some minor exceptions to strict discreteness.

It is easy to reject the concept of levels once the requirements on a successful theory of levels have been made implausibly strong. Even if the above suggested softening of requirements is accepted, however, it is still necessary to find a levels-criterion that is generally reliable, and this might not be possible after all. As we will see, there are significant problems with the standard levels-criteria.

4 Standard Criteria: Composition, Organizational Types, and Spatial Scale

Most treatments of levels of organization utilize several levels-criteria at once (Wimsatt 2007; Salthe 1985; Potochnik and McGill 2012). This is motivated by the fact that there is significant overlap between hierarchies generated by the usual criteria: as we ascend up the compositional hierarchy to ever more encompassing wholes, there tends to be an increase in spatial and temporal scale. But in fact, the levels defined by these different criteria often do not co-vary, and so a hierarchy mixing them together will certainly be inconsistent and will have non-discrete levels. This is sometimes exploited to demonstrate the incoherence of the levels of organization concept on the basis of any one levels-criterion's inconsistency with the others, as in Potochnik and McGill (2012). A more charitable strategy would make the levels of organization concept maximally coherent by considering candidate levels-criteria separately, in terms of the capacity of each one to define a hierarchy that is consistent and causally adequate.

4.1 Composition

Compositional or part-whole relations are perhaps the most standard levels-criterion among various hierarchy theories. The classical levels of organization concept is primarily based on composition: atoms are parts of molecules, which are parts of cells, which are parts of multicellular organisms, which are parts of populations, and so on. The main problem with the composition levels-criterion that I will focus on is that it is insufficient by itself to define levels "horizontally" across different individuals. A material composition criterion also runs into problems at levels where entities are functionally individuated. Even if compositional relations were causally adequate, then, it is not clear that there can be such a thing as a compositional *hierarchy* without some additional non-mereological principles.

Perhaps the most well-developed theory of compositional levels is Bechtel and Craver's account of levels of mechanisms (Craver 2007; Craver and Bechtel 2007; Bechtel 2008; see also Craver 2015), so I will take theirs as exemplary. In the mechanistic account, l_{i-1} entities are the *acting components* of l_i mechanisms. This differs from material composition in that entities that are only material parts of a mechanism but that do not contribute to its functioning are not parts of the individual that the theory classes into levels. On the basis of the mechanistic composition relation, Craver defines the interlevel relation as follows.

> *Interlevel*: "X's Φ-ing is at a lower mechanistic level than S's Ψ-ing if and only if X's Φ-ing is a component in the mechanism for S's Ψ-ing" (Craver 2007, 189; see also Craver and Bechtel 2007, 548).

The intralevel relation then becomes the following.

> *Intralevel*: "X and S are at the same level of mechanisms only if X and S are components in the same mechanism, X's Φ-ing is not a component in S's Ψ-ing, and S's Ψ-ing is not a component in X's Φ-ing" (Craver 2007, 192).[3]

[3] Note that with this formulation Craver offers only a "partial answer" (2007, 192) to the question of when two items are at the same level, in the form of a necessary condition ("only if"). However, other remarks seem to require there to be a sufficient condition as well. For example, it is said that like Wimsatt's (2007) levels of organization, "Levels of mechanisms are also loci of stable generalizations, and consequently can be seen as local maxima of regularity and predictability. This is because parts of the mechanism that make an intelligible (that is, regular and predictable) contribution to the behavior of the mechanism as a whole are identified at levels" (Craver 2007, 190; see also ibid., 195). It is unclear how one could generalize over levels in this way without there being some sufficient condition for two parts to be at the same level. Since no sufficient condition is given elsewhere, it seems justifiable to examine the stated definition as if it comprised more than a partial account of the intralevel relation—as a potential necessary *and* sufficient condition. This interpretation fits with Bechtel's (2008, 146 ff.) remarks on the intralevel relation.

Because mechanistic levels are defined entirely in terms of mechanistic parthood, there is no sense in which two different wholes that are not parts of a more encompassing whole are on the same level or different levels. Characterized in this way, levels are extremely restricted in scope. Not only do they not extend globally across horizontally distinct individuals that aren't compositionally related, but often they also will not extend locally across the parts of the same individual.

This can be grasped when we take more than one compositional partition[4] into account, as Eronen (2013) has pointed out. Let C_1 and C_2 be acting components of a mechanism M, and let S_1 and S_2 be subcomponents of C_1 and C_2, respectively. It is clear enough that on the mechanistic account C_1 and C_2 are on the same level, because they are components of M and not of each other. It is also clear that C_1 and M are on different levels because C_1 is a component of M. However, the level relations are less clear when it comes to S_1 and S_2, due to an ambiguity in the notion of component parthood. If S_1 contributes to the functioning of M, as evaluated by the "mutual manipulability" criterion (i.e., manipulating S_1 changes M and vice versa) (Craver 2007, 141), then S_1 is a component of M and they are on different levels. But then it will be the case *both* that S_1 and C_2 are on the same level, *and* that C_1 and C_2 are on the same level, since both pairs are components of M and not of each other. Assuming that the intralevel relation is transitive, which seems hard to deny, the contradiction follows that S_1 and C_1 are on the same level even though they are related as part and whole.

Alternatively, one can define components as "direct components," where direct components of a mechanism are not components of other components of that same mechanism (Eronen 2013, 1047). In this sense S_1 is a direct component of C_1, and C_1 is a direct component of M, but S_1 is not a direct component of M. But this ends up being overly restrictive. Only direct components such as C_1 and C_2 can stand in an intralevel relation. S_1 and S_2 are each on different levels than C_1 and C_2, respectively, but they are not on the same level as each other because they are components of different wholes—even if they are exactly the same type of thing with the same causal properties (e.g., two liver cells).

Bechtel (2008, 147) acknowledges that whether S_1 and S_2 are on the same level is "not well defined," and relates this to the fact that mechanistic levels are only well defined for mechanisms and their (direct) working parts. This would mean that the mechanistic account is usually restricted to only two levels at time, and even these level-relations might not hold when the phenomenon of interest is shifted up or down in partition. Applying the mechanistic account to more than two partitions, we get a bizarre branching hierarchy where there is no single level for subcomponents S_n, but many—namely, as many as there are intermediary partitions between subcomponents and mechanisms (see Eronen 2013, 2015).

It might be thought that this branching problem can be avoided by stipulating an additional rule that S_1 and S_2 are on the same level if they are the same number of partitions removed from some reference whole, such as M. However, in many cases

[4] A partition is a level-like separation of a single part and its encompassing whole. I use the term "partition" here as an alternative to "level," because whether partitions can successfully define levels is what is at issue. In the above symbolism, the partitions would include <M, C_1, and S_1> *or* <M, C_2, and S_2>—*not* <M, C_1 and C_2, and S_1 and S_2.>.

applying this rule will lead to undesirable consequences. In multicellular organisms, many of the constituent cells are components of tissues, which are components of organs, which are components of organ systems. Erythrocytes (red blood cells), however, are arguably direct components of the circulatory system. If we take the circulatory organ system as a reference whole, the same number of partitions rule dictates that erythrocytes must be at the same level as the heart, since they are both one partition removed from the circulatory system. But the heart and erythrocytes should not be at the same level: not only are they very different types of things, but the heart does not directly interact with erythrocytes, instead constraining their circulation. The same problem will arise whenever the reference whole contains a type of part that can exist at several of its different partitions: for example, molecules in cells, organelles and cells in multicellular organisms, and molecules or cells in ecosystems. Partition number is empirically too heterogeneous to capture either general types or causal structure for a compositional hierarchy.

In a more recent discussion of mechanistic levels, Craver (2015) favors the first, permissive construal of mechanistic parthood, and avoids contradiction by denying that the intralevel relation is transitive. When the transitivity assumption is dropped, C_2 can be at the same level as C_1 and also at the same level as S_1 without this entailing that C_1 and S_1 are at the same level as each other. However, denying transitivity has strange consequences for the intralevel relation. First, there will be multiple assignments of when C_1, C_2, S_1, and S_2 are on the same level for even the simplest mechanism having more than two partitions. Craver (ibid., 19) attributes this to the idea that levels are local rather than monolithic divides across nature, though the same severe non-discreteness will obtain locally. Second, the intralevel relation becomes highly inclusive: any two parts of a mechanism that are not related to each other as part and whole are at the same level, even if they differ widely in partition number, type, scale, and interaction structure. A single Ca^{2+} ion would be at the same level as a neuronal network in the hippocampus if both are acting components in the mechanism for generating spatial maps and the former is not a component of the latter (cf. Craver 2007, 165 ff.). What emerges from the new account is that, in fact, “sameness of level has no significance” for levels of mechanisms (Craver 2015, 19). Difference of level, by contrast, has the significance of telling us when two items do not causally interact. But this is highly restricted: members of levels are now understood to be tokens and not types (ibid., 18), and a token is only at a different level than the other token(s) to which it is specifically related as mechanistic part or whole. In my view, if sameness of level has no significance at all and difference of level applies only to tokens in the same vertical partition column, the rationale is unclear for continuing to refer to levels instead of just token composition.

These problems with mechanistic composition are only exacerbated by turning to material composition in order to define levels. Above the macromolecular partition, the entities of interest to science tend not to be individuated by their material composition. Complex systems are open systems in which there is a constant turnover of matter and energy. What persists over time in these systems is not a unique set of material parts, but rather a dynamic individual defined by a set of organizational or functional relations among its material parts. In contrast to a material compositional account, the mechanistic account in principle has no trouble conceiving such dynamic individuals as mechanisms because mechanisms are functionally individuated (see Machamer et al. 2000, 5–6; Bechtel 2008, 13 ff.; Glennan 1996). For this reason, among others, the account of mechanistic composition stays closer to the actual scientific explanations that invoke levels than any material composition account would. Hierarchies of material composition will diverge from scientifically recognizable hierarchies especially at higher levels, because material composition is not a primary individuating factor for functionally-defined entities (see Wimsatt 2007, 205).[5]

Both mechanistic and material composition accounts run into problems at higher levels, however.[6] If we think of an organism as a part, is it a part of its immediate physical environment or its population of conspecifics? The sense in which an organism is a part of a population cannot be determined using the same relations of material or mechanistic parthood as are available for lower levels. For example, "capacity to interbreed," the criterion in Mayr's biological species concept, is not a material or mechanistic composition relationship comparable to that between an organ and an organism, or between an organelle and a cell. Similarly, when organisms are considered parts of historically extended species-individuals, and thus of populations, this is a sense of parthood based on genealogical relations rather than causal, functional, or spatial relations as in material or mechanistic parthood. Being part of a historically-extended lineage is crucially different from being a causally active component in a present, existing system. A hierarchy that switches from one of these parthood concepts to another is therefore inconsistent in its levels-criterion. The defender of compositional levels might naturally wonder what is wrong with switching between specific parthood concepts for different levels as long as the overall hierarchy is consistently one of parthood "in general." But the trouble is that parthood in general is far too vague to unambiguously demarcate levels, and so this task will fall to a specific parthood concept. Once we start from a specific parthood concept, however, it won't be possible to switch levels-criteria at different levels without already presupposing a conception of levels, as it would require knowing *at which level* to switch levels-criteria.

Without a consistent parthood relation that is equally valid at higher levels, there can be no organismic level of composition, since two organisms cannot be said to be parts of the same whole. Moreover, even if we could say that organisms are parts of

[5] The idea that an ontological account of higher levels is normatively constrained by what would be recognizable to the sciences indicates that the two kinds of hierarchy distinguished earlier—ontological hierarchies and hierarchies of the sciences—might not be so independent after all. In particular, the presence of functions and functionally individuated entities is an important differentiating factor between the physical sciences, on the one hand, and the biological and social sciences, on the other hand, and it often correlates with differences of level in ontological hierarchies. It may be useful in some contexts to trace this difference between sciences as a difference of "level," reflecting different investigatory practices, interests, and/or different "levels of explanation." Thanks to an anonymous reviewer for pointing this out.

[6] Of course, the mechanistic account does not attempt to define a concept of level that can be used for systems like entire organisms, populations, or ecosystems, and probably none of its proponents would claim that such systems are mechanisms. The question, then, is whether there is some causal structure that should be captured by an account of levels but that is not accessible through the concept of mechanism.

a population on the basis of a consistent parthood relation, this would still fail to constitute a population level, since there is no generally valid sense in which two different populations are parts of the same whole. Two populations can be parts of the same species or ecosystem, or parts of different species or ecosystems.

In view of these difficulties, it is best to separate levels from compositional relations *per se*. At best, part-whole relations can define an interlevel relation, but will fail to define a consistent intralevel relation except in the most straightforward cases (i.e., C_1 and C_2 as l_{i-1} parts of M at l_i). To be precise, a compositional hierarchy will be unable to class individuals as being on the same level when (1) they are not straightforwardly parts of an encompassing whole, like organisms and populations, and (2) they are parts of an encompassing whole but are separated by intermediary wholes, like subcomponents S_1 and S_2. In addition to the vertical (interlevel) criterion, some additional horizontal (intralevel) criterion is needed in order to place such individuals on the same level. I mentioned above that the traditional levels of organization hierarchy is primarily based on composition. In fact, what is seldom noticed is that it is also based on a horizontal criterion that classes entities according to their organizational type. Two organisms are on the same level—the organismic level—not because they are parts of the same whole, but because they are the same *type* of individual. Likewise with populations and subcomponents of any kind. It is worth considering, then, whether combining composition together with organizational types might yield a viable hierarchy.

4.2 Organizational Types

Organizational types are level-like classes of individuals—usually, atoms, molecules, macromolecules, cells, organs, organisms, populations, communities, ecosystems, or some such variation. Organizational types enable one to do what compositional relations alone cannot do: namely, define a more consistent horizontal or intralevel relation. The above failed compositional intralevel relation is thus modified in the following way: individuals are on the same level not if they are parts of the same whole, but if they belong to the same *typical partition*. A typical partition would comprise different parts or wholes that resemble one another across many horizontally different individuals. Cells would form a typical partition in that they resemble one another, and in that—even if they are not parts of the same whole—they often have the same kinds of parts and are themselves parts of the same kinds of wholes. Perhaps, then, the typical cellular partition will suffice to define a cellular level of organization.

By all accounts, the criteria of composition plus organizational types generate a hierarchy that is closest to the classical levels of organization concept. Nevertheless, a hierarchy based on composition and organizational types faces problems of consistency and adequacy. As far as consistency, many of the concepts that are available to play the role of organizational types are less well defined than they initially seem, and may also originate from heterogeneous theoretical and practical aims. The diversity of kinds of vertical individuation between cells, organisms, and populations, for example, can undermine our ability to classify individuals into discrete levels. The concept of an organism extends over single-celled and multicellular organisms alike, which have very different biological properties. Between multicellular organisms and populations, moreover, there is a huge variety of kinds: slime molds that behave sometimes as populations and sometimes as multicellular organisms, highly coordinated colonies of various kinds, superorganisms, whole forests sharing one root system, and whole populations of fungi (*Armillaria bulbosa*) sharing the same genome, just to name a few. Such limit-cases suggest that there are too many different kinds of biological individuals to be able to fit all living systems into the levels of cells, multicellular organisms, or populations. In some cases, the same kind may also be defined differently in different investigative contexts—e.g., evolutionary versus physiological conceptions of the organism. Horizontal individuation between individuals of the same type is also not straightforward. For instance, for a great number of multicellular individuals, such as human organisms, it is now known that they depend on complex communities of symbiotic microbes for their normal functioning. In this case, the individual that digests, reproduces, and performs other functions is not just an organism belonging to *Homo sapiens*, but involves many levels of organizational types at once.

Consistency is not the most serious problem attending this levels of organization hierarchy. Arguably, it might be possible to modify and multiply organizational types to accommodate the above consistency issues.[7] Even if organizational types were consistent, though—and even if they were well-defined natural kinds—it is not clear that they could define a hierarchy that would be causally adequate. The reason is that the criteria for classifying entities into organizational types often have little to do with causal interactivity. Classifying some entity as a multicellular organism does not allow us to infer that it causally interacts only or primarily with other multicellular organisms on a multicellular-organismic level. Continuing the above example, the human organism directly interacts with populations and communities of microbes which are essential for many of its vital functions. The mixture of bacteria and other microbes in the gut may even be described as an "ecosystem" in which individuals belonging to several organizational types interact. Organizational types may be typical partitions, but individuals belonging to the same typical partition can differ significantly in their causal properties, and this is why organizational types are not translatable into hierarchical, "interactional" types.

It is true that organizational types are based on deeply entrenched scientific categories and have an undeniably useful role as organizing concepts, particularly in the life sciences. Like compositional relations, however, this role would appear to be something other than determining causal levels. It may be that compositional

[7] In documenting an evolutionary trend toward increased hierarchical structure in organisms, McShea (2001) usefully distinguishes between at least 10 organizational types based on their degree of internal nestedness and individualization (e.g., solitary prokaryotic cell, aggregate of prokaryotic cells, solitary eukaryotic cell, solitary metazoan, metazoan colony, etc.). Applied in the present context, McShea's typology is limited by two factors: (1) it does not include types for symbiotic associations between organisms having different internal hierarchical structures (ibid., 412), and (2) it is restricted to entities that are homologous to organisms in a free-living state (408). As a result of (2), the entities referred to by these different types are not composed of each another—for example, "higher-level" solitary metazoans are not composed of "lower-level" solitary prokaryotes. McShea's types are therefore not vertically arranged types in the same compositional hierarchy, but are organizational types for the organism level in different compositional hierarchies.

relations and organizational types together can serve as the basis for a general theory of organizational composition that would not involve any distinct notion of causal levels. For a theory of causal levels, however, a criterion more closely linked to causal interactivity is needed.

4.3 Spatial Scale

On a spatial scale hierarchy, entities are on the same level if they are similar in size and they are on different levels if they differ in size, relative to some specified threshold of difference. In the absence of some other complementary criterion, the size criterion is insufficient to define a hierarchy in both vertical and horizontal dimensions. For one thing, spatial scale—or any scale, in fact—is vertically continuous, whereas levels are discrete. One could introduce discontinuities into a continuous scalar ordering via a specified threshold of allowable intralevel variation, but this would be arbitrary, and then spatial "levels" would not capture any causally significant structure of the world. On the other hand, it could be that the systems of interest to scientists happen to be clustered around certain ranges of size scale, which could be used to specify discontinuities between levels in a non-arbitrary manner. It would then be an empirical question whether systems are in fact clustered around quasi-discrete scales or not.

A related concern is that a size ordering requires some reliable means of drawing spatial boundaries around individuals so they can be unambiguously measured, but determining such boundaries is less straightforward than it might initially seem. What is spatially included in the biological individual will differ relative to different perspectives: evolutionary, ecological, physiological, reproductive, immunological, etc. Where differences of perspective cannot be reconciled across different scientific practices and investigative interests, one encounters non-ontological sources of inconsistency for a theory of levels.

The more serious problem, though, is that spatial boundaries will suffer from some of the same difficulties as boundaries defined by material composition when applied to open, dynamic systems (see Sect. 4.1 above). This is especially—but not only—the case when one considers open systems that are spatially distributed, such as populations, communities, and ecosystems. Such systems are individuated not as much by observable spatial boundaries as by functional criteria, such as the strength of relevant interactions and their common participation in higher-level processes such as reproduction, predation, succession, or nutrient cycling (see Allen and Hoekstra 1992, 28).

Difficulties of consistency aside, the guiding idea behind the spatial scale criterion is about causality—namely, that entities of very different sizes do not causally interact. This does hold in a variety of cases where one entity can affect one another, but where they are so different in scale that the effect is small enough to be negligible—like a "drop in the ocean." Unfortunately, there are far too many counterexamples of direct causal interaction across widely different spatial scales for spatial levels to be a generally reliable guide to the segregation of causal interactions. A successful virus infecting a single organism can spread and eliminate an entire population. Small quantities of toxic substances can severely disrupt entire ecosystems. In the other direction, blue whales feed on krill and trees fix carbon. More often than not, spatial scale is just one relevant causal factor among others, but size differences hardly constitute a principled barrier to causal interaction.

5 Levels of Time Scales

Time scale denotes the characteristic amount of time it takes for system behaviors or processes to occur. It is defined by the rates or frequencies of system behaviors, or by relaxation times—i.e., the time it takes for a system to return a fraction of the distance to its equilibrium state following a perturbation of a given strength. A hierarchy of time scales is one in which faster or shorter-scale processes are at lower levels, and slower or longer-scale processes are at higher levels.

In biology, the idea of a time scale hierarchy has most often come up in the division between three broad domains of biological processes: metabolism, development, and evolution. While there are obvious qualitative differences between these processes, relative to each other they are differentiated very basically by rate differences that typically span several orders of magnitude. A time scale hierarchy was also in the background of Ernst Mayr's (1961) influential division of biological causes into ultimate (long-term) and proximate (short-term) causes—and, importantly in the present context, for Mayr rate differences are part of what secured the causal segregation of evolution and development. Conrad Waddington, similarly, represented the biological hierarchy as consisting of these three "time-elements" (metabolism, development, and evolution) whose distinctive coupling was, for him, "the main respect in which the biological picture is more complex than the physical one" (1957, 5).

A time scale hierarchy need not be defined in terms of these broad "organizational types" of processes, however, but can be abstracted as a pure scalar criterion for distinguishing more fine-grained levels of processes in any complex system. This type of more formal approach to hierarchy theory was most systematically pursued as part of a rich but largely forgotten discussion of the dynamical principles underlying hierarchical organization in systems theory through the mid to late twentieth century (see, for example, the edited collections of Pattee 1973; Whyte et al. 1969). Among these theorists were several ecologists working on hierarchy theory from the perspective of problems in ecology, who advanced time scale as the primary levels-criterion (O'Neill et al. 1986; Allen and Starr 1982; Allen and Hoekstra 1992; Levandowsky and White 1977). The following treatment of time-scalar levels is rooted in these ecological sources, but it aims to provide an embedding philosophical framework to match its empirical motivation.

The connection between hierarchical causal structure and rate differences can be grasped by first recalling why hierarchy tends to be present whenever there are complex systems (see Sect. 3). Complex organized systems will only arise and persist if they are stabilized against destructive influences from the environment, and this is facilitated by the compartmentalization of their constitutive dynamics into levels of stable sub-processes whose influence on one another is restricted (Simon 1962, 1973). Once this occurs, system behaviors at different levels have some dynamical autonomy from one another, which is another way of saying there is a causal segregation across levels. “Dynamical autonomy” or “causal segregation” here just means that the two processes do not have significant direct causal interactions, though they may or may not exhibit constraint relationships.

The way this relates to time scale is that dynamical autonomy can often be achieved through the segregation of process rates. The more two processes are separated as to their rates, the more their effects on each other will be attenuated. This is partially due to the fact that rate is already an individuating factor for what counts as a processes. Less trivially, though, it is because stable processes with a regular rate tend to be insensitive to causal or signal inputs that deviate too far from them in scale. This can be pictured schematically if we think of the stable process as a black box receiving inputs from another process and transforming them into outputs representing the amplitude of effects on its own behavior (see Fig. 1). The focal process has a certain regular frequency (within the l_i rate range), and when it receives an input signal having a similar frequency, the output amplitude is similar to the input amplitude. When it receives inputs having a higher frequency (from, e.g., l_{i-1}), however, the output amplitude is dampened. At a certain threshold of frequency difference (e.g., l_i and l_{i-2}), the output amplitude is effectively zero, meaning that one process does not appreciably affect the other at all.

As an example, consider a process of tree growth as compared with a process of photosynthesis occurring in the tree’s leaves (see O’Neill et al. 1986, 78). The process of photosynthesis will be sensitive to higher frequency or shorter-scale effects. The amount of light striking the leaves will vary on the scale of minutes and days due to factors like cloud cover and shading from other leaves. The process of tree growth, however, even though it depends on photosynthesis, will only register the average effects of these variations, since it occurs at a much slower rate. The

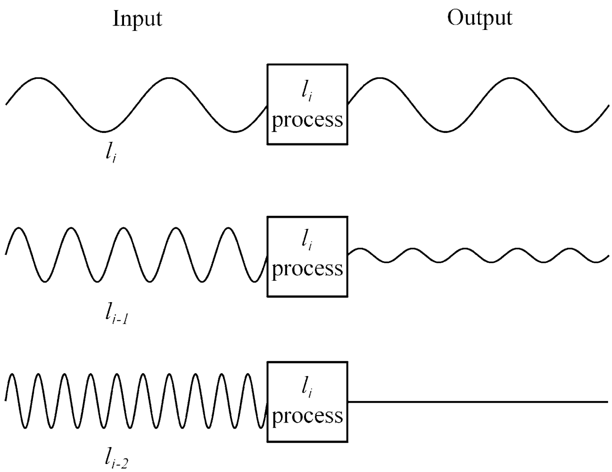

Fig. 1 An illustration of dynamical segregation due to rate differences, modified after O’Neill et al. (1986, 77). The basic idea is that the more an input to a process differs from the process in scale, the smaller its effects tend to be. Here, frequency represents rate or time scale, and amplitude represents magnitude of effect

width of the tree rings, indicating annual growth, will reflect an integrated response that dampens out the amplitude of the higher-frequency light variations. Due to their rate difference, the process of tree growth has relative dynamical autonomy from the lower-level process of photosynthesis.

The relation between these kinds of rate-separated processes is what Herbert Simon (1973) called "loose vertical coupling." A general way of characterizing loose vertical coupling is in terms of the mathematical relationships between equations governing different processes in the same system. For system processes whose time-evolution can be modeled by differential equations, many of the same variables will appear in equations governing the fast processes and the slow processes. However, what appear as variables in the slow process equations will appear as parameters in the fast process equations, while, inversely, variables in the fast process equations will appear as equilibrium or average values in the slow process equations. The variables in these cases are vertically coupled: they are the same variables, and so large enough variations might register in both the slow and fast processes. But their coupling is "loose" due to rate differences: each process is largely insensitive to the typical range of variations in the other, because the variations happen either too quickly or too slowly to make a difference. Examples of loose vertical coupling in complex systems can be found in a variety of different contexts: for instance, in the structure of interactions between populations with different generation times in an ecosystem (Levandowsky and White 1977, 103, 139), in the coupling of metabolic and epigenetic processes in cells (see Gorban and Radulescu 2007; Radulescu et al. 2006), in the coupling between ultradian and circadian rhythms in organisms (Lloyd and Rossi 1992) and even in the functional neural architectures underlying complex behaviors like handwriting (Perdikis et al. 2011a, b). In many cases, loose vertical coupling is a solution to the architectural problem that too much rate similarity can lead to destabilizing interference effects between processes, while too much difference can isolate the process dynamics from one another and make them more or less inert. Simon (1973) hypothesized that loose coupling makes complex systems both stable and flexible at the same time, because it allows selection to act on system modules without disrupting the entire system. From this perspective, biological time scale hierarchies can be seen as an architectural means of maximizing global stability and dynamicity, within the space of possibilities afforded by the relevant background conditions (physical, chemical, geological, etc.).

Granted that rate differences have this important role in natural hierarchies, still several concerns arise with the claim that rates should be used as a levels-criterion. There may be some processes that have widely different rates under different conditions. Population or ecosystem processes tend to be slower than organismic processes, but something like the extinction of a species or ecosystem can happen very suddenly (Potochnik and McGill 2012, 132). Such cases would appear to provide counterexamples where the same process should be at several levels at once. Here it is necessary to determine whether it is process *types* or process *tokens* that are being ordered into levels. For a process type, the rate ordering should be based on the average or characteristic rates of its tokens, instead of requiring that every token associated with l_i must always be faster than every token associated with l_{i+1}. For a process token, it is unlikely that it has widely different rates under different conditions, since rate regularity is part of what distinguishes some occurrence as a unified process in the first place. Depending on the investigative context, types and tokens can each be suitable members of level classes in different time scale hierarchies, as can types with different degrees of generality. Some situations call for greater generality and coarser-grained individuation of process types and causal interactions. Other situations call for less generality even to the point of only concerning the hierarchical relations between token processes. For example, a quite general question that is central to contemporary evo-devo research is how developmental processes affect evolutionary processes in biological lineages. By contrast, an ecologist might want to know whether a token process of predation is affecting a token process of ecological succession in a particular ecosystem. In both cases, time scale can operate in the same way as a criterion for demarcating causal levels, whatever the generality of the members of levels.[8]

Returning to the proposed counterexample, it is not clear that extinction is a process at all, as opposed to being a near-instantaneous *event*. A time scale hierarchy also need not absolutely prohibit interactions among differently scaled processes since vertically coupled processes are loosely coupled. Occasionally, large-scale fluctuations will cascade downward from higher levels and disrupt lower-level processes—e.g., an ice age or asteroid impact. Teggart (1925/1977) proposed distinguishing these occurrences as “events” as opposed to processes, and they are characterized by their infrequency relative to the time scale level where they are rooted, and hence also by their historical singularity (see Salthe 1985, 259). This distinction between processes and events helpfully captures the sense of hierarchy theory as relying on empirical generalizations over regularities, as well as its limitations in the face of irregular or catastrophic dynamics.

A time scale hierarchy also faces some of the same problems as spatial scale hierarchies. First, scale by itself is continuous whereas levels are supposed to be discrete. As noted above, however, non-arbitrary discontinuities can be introduced into a continuous scale if the entities to be ordered are clustered around certain values. If rate separation does play a critical role in establishing dynamical autonomy and stability then this should be expected—but only for local processes that can potentially interact. Two processes that always occur in completely different spatial regions are dynamically segregated not because of rate differences; rate differences have no such role to play in this case. Taken globally, ecological process rate differences tend to vary more continuously whereas rates of local processes are more discrete (Levandowsky and White 1977, 139). Quasi-discrete levels can therefore be defined on the basis of the clustering of processes around

[8] The type-token distinction could also be applied to the members of mechanistic levels: in describing the mechanism of long-term potentiation one may be interested in the mechanism type or in a specific mechanism token. However, more recently, Craver (2015, 18) has suggested that only tokens are members of mechanistic levels. In general, token hierarchies face fewer consistency problems but sacrifice inferential and explanatory scope. Note also that allowing members of levels to be types does not imply that types are being used as the levels-criterion. The specific problems raised in 4.2 with using organizational types as a levels-criterion therefore do not affect *compositional* hierarchies of mechanism types or *time scale* hierarchies of process types.

certain rate values in a given interactive context. As will be discussed below, this restriction leads to a very different notion of levels than the traditional global or universal one, in which level classes extend between different interactive contexts.

Time scale hierarchies also importantly differ from other hierarchy constructs in virtue of the category of items that are classed into levels. The individuals of a compositional hierarchy are material parts or functional acting components. Likewise, the individuals in a space-scalar hierarchy are spatially bounded objects. The individuals of a time scale hierarchy, however, are *processes*: it makes little sense to ask what the rate of an object is, because rates can only belong to temporally extended, dynamic items such as behaviors, activities, events, or processes. As Brian Goodwin observed in *Temporal Organization in Cells* (1963, 15): "The relaxation time criterion defines system in terms of process." In that work, Goodwin distinguished metabolic, developmental, and evolutionary levels of activity in cells solely on the basis of different relaxation times (no doubt influenced by his teacher Waddington):

> The use of a temporal criterion for attempting such a distinction […] implies a purely dynamic attitude to activities in the cell; that is to say, if a variable shows a "slow" rate of change, then it forms a part of the dynamic system whose relaxation time is of the same order of magnitude, and the nature of the variable is immaterial (12).

The idea of conceptualizing levels of organization as differential time scales generalizes this purely dynamic attitude. This approach has much to recommend it. In particular, the category shift from substances, objects, or material parts to processes enables time scale hierarchies to accommodate a feature that vexes the other hierarchy constructs—namely, that complex systems are often involved in many levels of processes at once. The difficulty can be resolved by specifying that it is system processes that are hierarchically segregated and not necessarily the system as whole. An individual substance may be involved in several distinct levels of dynamics, whereas a process already exhibits a dynamic coherence because it simply *is* a dynamics. That is why processes are much easier to order into causal levels than substances or whole systems are.

What are processes, then? As it turns out, there is a variety of ontological accounts of processes available (see Simons 2003; Seibt 2004; Steward 2013; Salmon 1984).[9] Not all accounts will fit the constraints set by the theoretical role that processes are supposed to play as members of time-scalar levels. Nevertheless, it is important to point out that this theoretical role underdetermines the choice of an account of processes. For example, processes can be viewed mathematically as functions or input–output maps, as in Fig. 1. Processes might also be sequences of dynamical states, or trajectories in state space. Alternatively, processes may be causally continuous series of events with some structural regularity. Or, in the vein of language-based ontology, processes might be the referents of action verbs having

[9] The individuation of processes is also discussed in the epistemological debate surrounding reliabilism. Reliabilism holds that a belief is epistemically justified iff it is the product of a reliable belief-forming process. A core problem, with several proposed solutions but no general consensus, concerns how to individuate "reliable belief-forming processes" (see Connee and Feldman 1998).

an imperfective grammatical aspect. In principle, any one of these characterizations is admissible as long as it can be made to fit the following conditions:

1. Processes must have measurable rates, and the rates must be regular and different in magnitude for at least some different processes.
2. Processes must be causally efficacious and cannot, as a category, be reducible to other ontological categories.
3. The individuation of processes cannot depend solely on those factors relevant to their role in time scale hierarchies—i.e., rate and causal segregation—for then the account would become circular and uninformative.
4. Like mechanisms, processes must be functionally individuated as opposed to being individuated by spatiotemporal region or material composition.

Regarding condition (1), for a process to have a measurable rate, it is enough for it to have (i) an identifiable beginning and end, (ii) a cyclical repetition structure, or minimally, (iii) any intrinsic property whose change over time can be compared against changes in properties outside of the process.

Condition (2) follows from the restriction to ontological levels representing causal structure. If levels were understood purely as heuristic or pragmatic devices, then a hierarchy of processes could conceivably be interesting for some scientific purposes even if processes were not mind-independent or were categorially reducible—e.g., reducible to changes in properties of objects over time.[10] Conversely, a time scale hierarchy of processes is compatible with either the categorial reducibility or irreducibility of objects.

Condition (3) deserves some comment due to the fact that processes are often understood to be intimately connected to causation—for instance, in Salmon's (1984) process theory of causation. The trouble is this: if processes are individuated in some way by causal interactions, and causal interactions are also what hierarchy theory aims to represent, then one would need to already know the targeted interaction structure in order to individuate processes and assign them to levels. But then the level assignment would provide no additional causal information. Fortunately, this is not the situation: not all causal interactions are relevant to the construction of a theory of levels, but only causal interactions between putatively interlevel items. As a consequence, the only interactions that cannot be presupposed in modeling a hierarchy of processes are the interactions *between* processes. As long as processes can be individuated at all, such that one can operationally distinguish between inter-process causation and intra-process causation, causal relations can play a role in individuating processes. There seems to be good reason for thinking this is the case. There are many examples of processes that are grasped as units before they are understood as interactions between entities—e.g., raining, growth, mitosis, fermentation, metamorphosis, the beating of the heart, etc.—even if processes also have an internal causal structure.

Finally, condition (4) requires that processes be functionally individuated. For an item to be functionally individuated means that it is individuated by its effects and/

[10] For an argument against the categorial reducibility of certain thermodynamic processes to changes in the states of objects, see Needham (2013).

or its functional organization. The difficulty motivating this requirement is that of distinguishing the relevant from the irrelevant parts of an object or process for existing scientific theories and explanations. For example, photosynthesis tends to have a certain biochemical composition, but the activities of same biochemical components can fail to constitute a process of photosynthesis—e.g., if the temperature exceeds the threshold of protein lability. If the process were individuated by its material composition, then "photosynthesis" would have widely different rates and causal properties at different times. Spatiotemporal location also cannot be what individuates processes because two processes can occupy the same spatiotemporal region while differing in their rates and causal properties: e.g., cellular photosynthesis and growth. It is more plausible to think that something counts as an instance of photosynthesis in virtue of its functional biological properties—for example, its metabolic role in plants or its ecological role in primary production.

Without functional individuation, it is unlikely that processes could form a hierarchy that would be germane to the explanatory operations of the existing sciences that study complex systems. As members of levels, processes are similar to mechanisms in this respect and dissimilar to material or spatial parts (see 4.1). Aside from this common point, though, the process-centered approach differs in several ways from mechanistic ones (see Dupré 2012, 2013). The most basic difference that is relevant for the issue of levels is that processes comprise a general ontological category, whereas mechanisms are categorially hybrid items that are specifically invoked in certain types of scientific explanation. As a result, process hierarchies can have more processes at levels, including at organism partitions and higher. A process can also be at a level without being an explanans of some phenomenon, if "process" is just the appropriate descriptive categorization of what the item is. Ontogenesis is a process, for example, but it is not a mechanism for some phenomenon in any obvious way. These differences make process hierarchies more general while also allowing them to more closely capture the sense of levels of organization as based on a descriptive "ontological architecture" and not only on a certain form of explanation.

To recapitulate, then, compared to the other hierarchy constructs that have been reviewed, a hierarchy of processes ordered by time scale presents several advantages. Because processes can be functionally individuated, one avoids the problems native to hierarchies of size scale and material composition of individuating higher-level items. Unlike both material and mechanistic compositional hierarchies, a time scale hierarchy is capable of defining levels across horizontally different individuals and above organismic partitions. The time scale hierarchy and the principle of dynamic segregation it is based on also extend over processes that are hierarchically related but not compositionally related in any straightforward way, which belong to the same local interactive context, such as climate processes and population processes in an ecosystem. Unlike the combination of composition and organizational types, the time scale hierarchy is more causally adequate—i.e., it describes a structural segregation of causal interactions. It gains this advantage over each of the other hierarchy constructs by its association with the principles of dynamic stability, which allows it to get closer to causal interactivity without circularly invoking causal interaction as the levels-criterion. As a consequence, however, it leads to a conception of levels that is more modest than the traditional notion of levels of organization.

6 Conclusion

The traditional notion of levels of organization has received strong criticisms from a number of philosophers for the kinds of reasons we have seen (Potochnik and McGill 2012; Craver and Bechtel 2007; Bechtel 2008; Ladyman and Ross 2007; Eronen 2013, 2015; Rueger and McGivern 2010). While I agree with many of these criticisms of the traditional conception, they do not go so far as to demonstrate that there can be no alternative conception of levels that fulfills the primary ontological aim of hierarchy theory. The foregoing account in which levels are time scales of processes is what I take to be the most promising approach to causal levels. In capturing a sense of levels that is causally adequate, however, this approach had to give up any strong typological element to levels-classifications. Compare: "process *x* takes place at the cellular level" versus "process *x* takes place at an average rate of 1 cycle every 33 s." A process rate has no significance except in relation to other process rates within the same local interactive context. Assigning a process to a level might tell us something about how a process is likely to behave, but not about what its essential properties are. Time-scalar levels are even farther from natural kinds than levels of organizational types are. In many ways, then, the hierarchy of time scales amounts to a "deflation" of levels in the traditional sense, as in Eronen (2013, 2015) and Potochnik and McGill (2012), while still maintaining—*pace* these critics—that there is some hierarchical structure to be found, in general, in local contexts of interaction.

There may certainly be contexts in which concepts of size or composition can do the work of a hierarchy construct without involving levels in any distinct way. It is not clear, for instance, that a notion of levels rather than composition and scale will always be specifically necessary for analyzing local cases of reduction or putative downward causation (see Eronen 2013). There is also nothing wrong in principle with retaining some version of the traditional levels of organization concept for its heuristic or pedagogical value. The combination of composition and organizational types can likely remain useful in the form of a theory of organizational composition, so long as it is recognized that it does not define causal levels in a rigorous sense. To get at a notion of levels that is consistent and causally adequate, however, it is necessary to turn from typological to dynamical criteria.

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