Forms of emergent interaction in General Process Theory

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Abstract General Process Theory (GPT) is a new (non-Whiteheadian) process ontology. According to GPT the domains of scientific inquiry and everyday practice consist of configurations of 'goings-on' or 'dynamics' that can be technically defined as concrete, dynamic, non-particular individuals called general processes. The paper offers a brief introduction to GPT in order to provide ontological foundations for research programs such as interactivism that centrally rely on the notions of 'process,' 'interaction,' and 'emergence.' I begin with an analysis of our common sense concept of activities, which plays a crucial heuristic role in the development of the notion of a general process. General processes are not individuated in terms of their location but in terms of 'what they do,' i.e., in terms of their dynamic relationships in the basic sense of one process being part of another. The formal framework of GPT is thus an extensional mereology, albeit a non-classical theory with a non-transitive part-relation. After a brief sketch of basic notions and strategies of the GPT-framework I show how the latter may be applied to distinguish between causal, mechanistic, functional, self-maintaining, and recursively self-maintaining interactions, all of which involve 'emergent phenomena' in various senses of the term.

Keywords Process ontology · Mereology · Emergence · Mechanism · Causation · Interaction · Self-maintenance · Feedback

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1 Introduction

The philosophical discussion of emergent features has a long history, reaching back to the Presocratics. In twentieth century philosophy, however, the debate about emergence has taken some rather curious turns. In view of the increasing success of reductionist science and the notion of causality associated with the latter’s atomist, particularist presuppositions, proponents of the ontic reading of emergence—the so-called vitalists, such as H. Driesch, H. Bergson, or S. Alexander—took to postulating non-causal forces in nature. Those who did not want to employ such extreme measures, such as C. D. Broad, found themselves forced to turn to a more moderate account of emergent phenomena in terms of unpredictability relative to a lower level of description. In this way the default interpretation of the notion of emergence gradually shifted from the ontic to the epistemic reading. In 1961 E. Nagel contrasted an account of “ontological” emergence, as the existence of causal properties of complexes that are not “derivable” from the laws of the causal properties of the components, with an epistemological account of emergence as the unpredictability of the generation and behavior of a complex phenomenon. This distinction in effect blurred the contrast between the ontic and epistemic reading, and, moreover, invited a further adjustment from absolute unpredictability to unpredictability relative to a state of scientific advance or, alternatively, factual unpredictedness. In essence these adjustments relegated the discussion of emergence to the “context of discovery” of scientific theories, pushing it out of the mainstream of discussion in philosophy of science. With a few notable exceptions quoted below, it was only late in the twentieth century that philosophers of science rekindled their interest in emergence, reacting to new developments in science itself such as chaos theory and the theory of self-organization. But this “re-emergence of emergence,” as several authors dubbed it, initially was not conducive to a clarification of ontic emergence per se, since at first it centered on a special and metaphysically particularly problematic case of application, the mind-body problem. A chaos-theoretic description of the brain seemed to allow for an easier association of neurophysiological entities and mental entities. But the new descriptive strategies of chaos theory as such are not sufficiently strong to immunize accounts of emergent mentality against J. Kim’s influential “exclusion argument.” Kim argued that emergent mental causality amounts to a violation of the causal closure of the physical domain. Whatever its independent merits, Kim’s case against non-reductive physicalism in philosophy of mind distracted the debate from the much more general question about ontic emergence as a general relationship between complexes and their components. Only in the last decade philosophers of science reminded themselves that emergence can be investigated as a claim about natural entities described by physics alone.

1 Cf. Mourelatos (1986)
3 Cf. e.g., Kim (1993).
Researchers in analytical ontology so far have been slow to enter the arena. The narrow focus on mental causation certainly provided a good reason for this reticence: as long as emergence was discussed as a claim about the ontological status of mental entities, it seemed to be secondary to the main line of ontological research with its typical focus on the analysis of material and concrete entities. In addition, ontologists typically investigate concepts for entities and relationships (such as persistence, causation, thing, disposition) that—unlike the notion of emergence—are deeply entrenched in everyday and scientific thought.

However, there is also a ‘bad’ reason for the fact that emergence has not been a core theme in contemporary analytical ontology. Notwithstanding new techniques of formal modeling—or, in fact, even supported by ‘standard readings’ of predicate logic—analytical ontology still follows the traditional research paradigm that has dominated ontological research since Aristotle. This research paradigm can be compactly defined in terms of a dozen or so fundamental presuppositions; together these premises create a theoretical bias in favor of the ontological primacy of ‘thing-like’ basic ontological entities, that is, concrete, countable, particular (i.e., uniquely located) individuals, called ‘substances’ or ‘objects’. The traditional ‘substance paradigm’ operates as a problematic restriction in the solution space of ontological theories, rendering many new questions arising from contemporary science ab initio as ‘absurd’ and thus inaccessible from within mainstream ontology. For example, within the substance paradigm, it is ab initio absurd to investigate whether quantum-physical entities could be interpreted as indeterminately located individuals. Moreover, several well-known core problems of ontology—notably the ‘problem of individuation,’ the ‘problem of persistence,’ and the ‘problem of universals’—are actually generated by the presuppositions of the substance paradigm. These are problems ontology would not need to have. On the other hand, there are problems that should take center-stage in ontology but are unlikely to do so as long as the substance paradigm reigns. Emergence is a case in point here. To offer a rough illustration, mainstream ontology presupposes P1 and P2:

(P1) the world is an assembly of concrete, countable, particular individuals (‘substances’ or ‘objects’),
(P2) all and only singular individuals are the logical subjects of one-place properties.

But then the question whether there could be emergent one-place properties of groups of basic objects (e.g., ‘rotates’) will be found strangely incongruent, since emergent one-place properties apparently lack a proper logical subject.

To abandon the substance paradigm, at least partially, is thus the first necessary step towards an ontological theory of emergence. A second step, if not necessary so at least heuristically useful, is to insist on a distinction between philosophy of science,

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4 Detailed analyses of claims about emergence so far have been supplied mainly by philosophers of science rather than by ontologists, see e.g., Cunningham (2001), Hooker (2004), Humphreys (1997), Rueger (2000), Wimsatt (1986, 1997), Saywer (2004), Smith and Stevens (1996), and Soto and Sonnenschein (2006).
metaphysics, and ontology, and to delineate how much (or how little) is to be expected of an ontological investigation of emergence. That there are (or fail to be) genuine cases of emergence is a conceptual claim based on empirical phenomena. While philosophers of science debate the truth of this claim relative to various definitions of emergence (or reduction) and relative to various empirical data, ontologists have no business with the empirical part of the question. Rather, ontologists investigate what kind of structure we could rationally assign to our world, if certain claims about emergence were true. In general, ontology is the “metaphysically neutral” investigation of possible structures of the domains of natural and scientific languages.\footnote{More technically speaking, it is the task of metaphysics to determine the intension of ‘truth’ and ‘truth-in-L’ and the task of L-users (e.g., scientists) to determine the extension of ‘truth-in-L,’ while an ontological theory is a domain theory for a natural or scientific language L, specifying structural descriptions of the “truth-makers” of those sentences of L that are accepted as true by L-speakers; cf. Selb (2000b; 2004b).}

The purpose of this paper is thus to offer an ontological interpretation of some statements about (ontological) emergence in the sense of devising a structural description of entities that these statements could be taken to be about if they were true. I will suggest that claims about emergence are best interpreted within a process-ontological framework based on activity-like dynamics called ‘general processes.’ That emergence requires a process ontology has been argued both by the ‘older emergentists’ such as Herbert Mead or Samuel Alexander, as well as by more recent authors including proponents of interactivism. But such arguments are frequently based on a vague and ambiguous notion of process. In contrast, I will make use of a formal process-ontological framework, the ‘theory of general processes’ (GPT), a mereology with non-transitive part-relation.\footnote{The basic ideas of GPT have been developed stepwise, in different terminological guises and with some technical modifications, in Selb (1990, 1995, 1997, 2000a, 2002, 2004a), and, in particular, in Selb (2004b). Some of the ideas mentioned and developed in Selb (2003) also are foundational for R. Campbell’s notion of a “generic process” (see this volume) which, however, differs in certain respects from the category “general process” in GPT. Whatever its epitath, the categorical definition of my notion of process has not changed since its first publication in 1990.} After sketching some of the basic constructional ideas and strategies of GPT, I show how the formal framework of GPT can be used to differentiate between various types of interaction dynamics. One of my primary aims will be to show that talk about “mechanisms” and “emergent phenomena” is ‘made true’ (can be taken to denote) by distinctive sections in a graded spectrum of forms of emergent interactivity.

2 General processes

Pointing to quantum field theory or complexity theory, some philosophers of science have called for the abandonment of traditional ways of conceptualizing natural entities, such as the ‘particle picture’ or ‘atomism.’ But the theoretical work involved in ontological recategorization proper is easily underestimated.

2.1 Ontological recategorization

From the ontologist’s point of view, the mere mention of suggested replacement terms, such as ‘structure,’ ‘field,’ ‘event,’ or ‘process,’ has heuristic value at best, since the
intuitive meaning of such highly general nouns is all too vague. As tedious as it may
appear, conceptual revision must take the detour into ontological inquiry where cat-
gory terms are defined sufficiently precisely so as to be of use for the description of
what scientific statements are about. Ontological categorization is a complex task that
must be guided by the following three aspects of ontological methodology.

First, an ontology is a theory—it is a domain theory for a natural or scientific
language L, specifying structural descriptions of the "truth-makers" of those sen-
tences of L that are accepted as true by L-speakers. All basic descriptive terms,
in particular terms for types of domain entities and their relationships, should be
well-defined (explicitly or implicitly). Types of entities, so-called categories, (e.g.,
substance, monad, trope, event, attribute etc.) are commonly characterized in terms of
lists of so-called category features (e.g., an entity is said to be concrete, particular,
persistent, simple etc.), and it is these category features that carry the actual definitional
burden. To illustrate, a mere call for the redescription of nature in terms of 'events'
will not do, since for some ontologists events are abstract and general entities, for
others they are concrete and particular, for some they are instantaneous, for others
temporally extended, and so forth.

Second, ontological category terms like ‘substance,’ ‘property,’ ‘trope,’ ‘occasion,’
‘mode,’ ‘relation,’ ‘state of affairs,’ ‘process,’ ‘event’ etc. are theoretical terms, even if
they have gained everyday currency in common sense discourse. They label the types
of theoretical entities that are postulated as denotations for the sentences of a lan-
guage or scientific theory L. Theoretical entities in science (e.g., harmonic oscillators) have
models (e.g., the ideal spring), and the same holds for theoretical entities in ontology.
Models furnish theoretical terms with the non-structural components of their meaning
that matters crucially for the ‘viability’ of these terms. The model for substances are
things, for example, and much of the longstanding popularity of substance ontology
derives from the central function of things in practical contexts.

Third, an ontology is an explanatory theory—just as scientific theories postulate
theoretical entities in order to explain certain observable events, ontological theories
postulate theoretical entities in order to explain why L-speakers are justified in drawing
certain inferences or in refraining from doing so. Ontologies are thus to be evaluated
in terms of their explanatory success—even if it has seemed ‘natural’ for a long time
to describe the world as an assembly of thing-like entities, the explanatory scope of
such schemes is quite limited. This holds especially with respect to inferences licensed

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10 More precisely, an ontological theory has the form of the quadruple $<M, \overline{T}_M , \overline{f}, \overline{L}>$: it specifies an
assignment $\overline{f}$ which correlates the elements of a class $L$ of L-sentences with structures of the domain of inter-
pretation $M$ as described by a domain theory $\overline{T}_M$. For a more detailed reconstruction of the methodological
stance of analytical ontology as "theory of categorial inference," see Seibt (2000b).

11 The notion of a ‘model’ can be defined more precisely by “semantic ascent” in terms of logical relationships
between terms for theoretical entities and models.

12 These inferences are ‘material inferences’ of a very general kind, which I have called ‘categorial inferences’ (Seibt 2000b).
For example, if ‘Kim is a woman’ is true, then it follows that ‘it is impossible that
Kim is both at home in her village and at work in the city at the same time’ is true, while ‘it is impossible
that a woman is at home in the village and a woman is at work in the city’ is false. Ontologists traditionally
have explained such inferences by claiming that ‘Kim’ denotes a particular (i.e., uniquely located) and ‘is
a woman’ denotes a general entity.
by contemporary scientific theories, which are typically focused on dynamic aspects, i.e., on causes, modes, and consequences of occurings.

2.2 Non-particular individuals

The contemporary debate has seen its share of competitors to traditional substance ontologies, notably Whitehead's event ontology, trope ontologies, 'hunk' ontology, stage ontologies, and ontologies based on states of affairs. All of these approaches reject some of the presuppositions that characterize the substance paradigm, e.g., the presupposition that only non-predicable entities are particular, or that all concrete individuals are identical through time rather than extended in time. But these alternative approaches each retain several presuppositions of the substance paradigm and thus are "revisionary ontologies" only to a degree.\(^{13}\) Moreover, there is one 'axiom' of the substance paradigm that, as far as I can see, no post-Cartesian ontology has rejected so far, including extant approaches to process ontology.\(^{14}\) This is the assumption that all concrete individuals are particular entities. A concrete individual is a 'this,' a reidentifiable entity of which something can be predicated and which occurs in spacetime. Such concrete individual entities traditionally have been taken to be particulars, i.e., entities that (i) each have a determinate unique spacetime location and (ii) have this location necessarily since they are individuated in terms of its location.\(^{15}\)

The intuition that all concrete individuals (i.e., all basic constituents of nature), necessarily have a unique determinate location in space at any point in time is the most central commitment of the substance paradigm. This intuition is not based on a 'law of thought,' however, but merely on theoretical habituation. We can replace the particularist conception of individuals with a view of individuality that focuses not on location but on 'specificity-in-functioning' in the widest sense of 'functioning,' i.e., focuses on the dynamic role of an entity (e.g., an activity) within a certain dynamic context. The practice of individuating aspects of nature in terms of what is happening or going-on, rather than where, is just as well-entrenched in our common sense and scientific reasoning as the practice of individuating by location. For example, we employ function-based individuation in the following sentences about concrete occurrences of activities and stuffs: 'it is snowing, not raining,' 'the radiation has decreased by 50%,' 'the erosion runs all along the coast,' or 'the fire spread rapidly,' or 'there's water in the next valley.'\(^{16}\)

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\(^{13}\) One notable exception is Pranel's (1993, 2006) theory of primary states of affairs.

\(^{14}\) For the latter cf. e.g., Whitehead (1929), Rescher (1996), Stout (1997).

\(^{15}\) An entity x has a determinate unique spacetime location just in case it holds that for any point or moment in time at which x exists, it is located in precisely one bounded, connected spatial region. (A region that is 'connected' in the topological sense might be 'multiply connected,' i.e., include holes.) That x and y have different locations is commonly said to be sufficient and necessary for their numerical difference, i.e., for their being two particulars. Note, though, that some trope ontologists allow for particulars ('abstract particulars') to be spatially superposed at a time; to include this position we should thus rather say that location is always a necessary component of the identity conditions of particulars.

\(^{16}\) Historically viewed, this second sense of individuality as specificity-in-functioning has been discussed in the Aristotelian tradition in individualistic interpretations of the "ex tenein," such as Duns Scotus' "haecceitas." Leibniz' so-called principle of the identity of indiscernibles can count as an attempt to revive the
2.3 The model: subjectless activities

The activities just mentioned have been called "subjectless activities," since they apparently have no logical subject—they are not the doings of a person or thing (or of a collection of persons or things). Subjectless activities provide a suitable model for any ontological category of non-particular concrete individuals, i.e., for concrete entities that are not individuated in terms of their location and/or are not taken to occur necessarily in a unique spatial location at any particular point in time. I have used subjectless activities as the model for a new category labeled 'general processes,' pointing at seven characteristic features of subjectless activities that the new entity sort shares with its model. (i) Subjectless activities are occurrences in their own right rather than modifications of persons or things—like things, and unlike properties and relations, they are independent in the sense that their occurrence in space and time does not necessarily require the existence of a different sort of entity they occur in or qualify (they may of course be constituted or caused by other entities). (ii) Subjectless activities are temporally extended—there are no instantaneous activities. (iii) However, quite unlike things, and much like stuffs (water, wood, etc.) subjectless activities occur in space and time both with indeterminate and with determinate locations (cf. ‘there is lots of rain in Denmark’ versus ‘on Oct. 12 it rained in Aarhus between 8 a.m. and 1 p.m.’). Most importantly, a subjectless activity does not necessarily occur in a unique spatiotemporal location—ontologically speaking, a subjectless activity is not a particular. While things are located at any time in one place only, subjectless activities are multiply locatable like properties and stuffs—they can, and mostly do, occur in many places at the same time. ‘It is snowing’ can be true of many different scattered regions at the same time. (iv) Subjectless activities also resemble stuffs in that they are not "countable," i.e., they do not come in "natural" countable units but only measurable in portions or amounts (e.g., an hour of snowing, 1,000 lumens of...
light), which then may be counted. (v) Like stuffs and properties, subjectless activities are not necessarily determinate in all of their qualitative or functional aspects—ontologically speaking, they are determinables. (vi) Subjectless activities are individuated in terms of their roles within a dynamic context, rather than by their location in space and time. (vii) Subjectless activities are dynamic but they are not changes. Constitutive 'phases' of their overall dynamicity (for example: the change of place of every single flake constituting the dynamicity of the snowing) contribute to the functionality of the activity but not as temporal stages or phases. In contrast to developments, activities have no internal temporal differentiation.

2.4 General processes

These seven aspects of subjectless activities dovetail with the main category features of the new category or entity type called ‘general process.’ General processes are independent, individual, concrete, spatiotemporally extended, non-particular, non-countable, determinable, and dynamic entities, in the traditional senses of these predicates as just sketched and more precisely defined in the formal framework of the theory of general processes (GPT). Each of the mentioned category features is well-known from the ontological debate, but their combination is new (in fact, the combination is outright inconceivable as long as one chooses to remain spellbound by the presuppositions of the substance paradigm).

General processes are the ontological counterparts not only of statements about subjectless activities but also of statements about things, stuffs, events, properties, actions, relations, persons, etc. In other words, any concrete individual is a general process, since the logical differences between statements about, say, things and stuffs, or activities and events, can be accounted for in terms of ontological differences among varieties of general processes. In GPT these differences are articulated within a typological matrix based on the values of five classificatory dimensions; one of these I shall briefly sketch now and mention the remaining four in Sect. 3.5 below.

2.5 Mereological signatures

Already Aristotle observed that common stuffs such as water and flesh are “like-parted (homoeomerous) bodies”: they are “composed of parts uniform with themselves.” As various contemporary authors observed, there is an analogous mereological condition for activities, holding with respect to time—they are ‘monotonous’ or ‘homogenous’ occurrences where beginning, middle, and end of the interval of their duration are ‘of the same nature as the whole.’ Just as any spoon of a puddle of water is like the whole, namely, an expanse of water, so any minute of an hour of snowing is like the

\[\text{Cf. History of Animals, 487a2. Aristotle speaks of ‘homoeomerous’ entities, which could be translated as ‘similar-parted’ (of a similar kind) and contrasted with ‘like-parted’ (homomerous, of the same kind). This difference has been neglected in the discussion of ‘homogeneous’ entities and here I will do so as well.}
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\[\text{Cf. e.g., Vendler (1967), Verkuyl (1978, p. 244), Mourelatos (1978, p. 431).}\]

\[\text{Springer}\]
whole, namely, a period of snowing. Thus we can formulate the following general mereological condition:

**Like-partedness or homerity**: An entity of kind $K$ is homerous iff all of its spatial or temporal parts are of kind $K$.

Upon a closer look, however, activities expresses an even more remarkable mereological condition than like-partedness. Since activities are purely 'functionally' individuated, it does not make sense to distinguish between an activity and its nature—an activity is a concrete type of dynamics. Of course we may say that every minute of an hour of snowing is of the same nature as the whole, but then we are talking not about the activity of snowing at all, but rather about a particular spatiotemporal amount of snowing. For the activity itself, the following holds:

**Self-partedness or automerity**: An entity $E$ is automerous iff for any spatiotemporal $r$ it holds that if $r$ is a subregion of a spatiotemporal region $R$ in which all of $E$ occurs, then $r$ is a region in which all of $E$ occurs.\(^{22}\)

Some entities are less homogenous or monotonous than others (e.g., mixtures such as fruit salad and repetitive sequences such as folding shirts), and there are entities for which it holds that there are no parts like them or containing them, namely, things and events (developments). For example, computers and symphonies are not like-parted: no spatial part of my computer is a computer, and no temporal part of a baptism or a symphony is again a baptism or symphony; and similarly for self-partedness.

The features of like-partedness and self-partedness can thus be generalized in two respects: first, with respect to dimensionality, and, second, with respect to degree:

**Maximal, normal, minimal homerity**: An entity $\alpha$ of kind $K$ is maximally/normally/minimally like-parted in space (time) iff all/some/hone of the spatial (temporal) parts of the spatiotemporal extent of $\alpha$ are of kind $K$.

**Maximal, normal, minimal automerity**: An entity $\alpha$ is maximally/normally/minimally self-contained in space (time) iff a spatiotemporal region in which $\alpha$ exists has only/some/hone spatial (temporal) parts in which all of $\alpha$ exists.

Figure 1 below offers a graphical illustration of spatial and temporal automerity.

General processes in GPT are sorted into different types in terms of their like-partedness (homerity) and self-partedness (automerity) in space and time.

For example, (i) general processes denoted by statements about activities (e.g., the process denoted by 'it is snowing') are type-1 processes, that is, they are temporally maximally automerous (and spatially unmarked); (ii) general processes denoted by statements about stuffs (e.g., the process denoted by '... is water' and 'Water (is) ...') are type-2 processes, i.e., they are spatially normally automerous and temporally maximally automerous; (iii) general processes denoted by statements about spatial amounts of stuffs ('this expanse of water') are type-3 processes, i.e., they are spatially normally homerous but minimally automerous, and temporally maximally

\(^{22}\) Self-partedness is a coherent concept only within a mereology with non-transitive part-relation, cf. the following section. For a theory of persistence based on self-partedness see Selby (2007).
The horizontal and vertical axes represent orderings in space and time, here on purpose unassigned: if the horizontal dimension is time, the graphics represent temporal automerity, and vice versa.

All general processes are thus self-parted and like-parted, but to different degrees in different dimensions. GPT thus is turning the tables on the substance paradigm where non-countable, non-particular entities such as stuffs and activities (e.g., water or snowing) typically have been analyzed in terms of countable and uniquely located entities such as portions or quantities of stuff and bounded developments (as denoted by e.g., 'this puddle of water,' 'a dl of water,' or 'snow flake's S1's moving from p1 to p2'). In contrast, in GPT the countable is treated as a subform of the stuff-like or non-countable: a thing is treated as the minimal amount of an extremely inhomogenous stuff, as it were, and a development as the minimal amount of a least monotonous activity.

In sum, general processes are concrete dynamics that are best understood on the model of subjectless activities. Whereas traditional substance ontology has tied individuality to particularity or necessary uniqueness of location, and consequently could ascribe individuality only to concrete entities that are determinately located in bounded regions and occur in countable units, in GPT individuality is tied to specificity-in-
functioning and thus can be ascribed to concrete entities that are multiply locatable and ‘stuff-like,’ i.e., that do not occur per se in countable units. Intimately connected with these two intuitions about individuality are two notions of concrete being—being as being placed versus being as ‘acting’ or ‘functioning.’ Just as the ‘where’ of being placed can only be made sense of relative to a spatio-temporal context, so the ‘how’ of acting can only be articulated relative to a dynamic context. The next section will sketch the essential ideas for a formal description of general processes and their relationships.

3 Basic formal strategies of GPT

GPT is the theory of individuals implicitly defined by the axioms and definitions of a mereology called GPM joined with principles of GPT. For present purposes it will suffice to sketch five special constructional features of GPT.

3.1 Mereology with a non-transitive part-relation

Ontologists commonly assume that the meaning of the part-whole relation is formally articulated by the axioms of “classical mereology.” Upon a closer look, however, the relation modeled by systems of classical mereology is the relation ‘is a part of’ which holds for particular (location-individuated) and countable entities only. (That this clandestine restriction to countable particulars has gone virtually unobserved is yet another powerful indication of the theoretical bias effected by the substance paradigm.) In contrast, the relation ‘is part of’ can be used with all sorts of arguments, both location-individuated (particular) individuals and functionally individuated (non-particular) individuals. Here are some real life examples: “blogging is part of life,” “Russia is part of the West,” “Music is part of God’s universe,” “All I See Is Part Of Me” (book title), “Learning to negotiate is part of the advocacy process,” “my heritage is part of who I am,” “Is part of your college education missing?” “Boston is part of the Islam,” “Loss is part of living,” “Syria is part of the solution,” “looking immaculate is part of what I do,” “having a good signed contract is part of running a professional business,” “Pain is part of running marathon,” “Hopping too is part of running.” As usages like these convey, the expression ‘is part of’ states a highly general relation of functional ‘belonging with’ (both as contributory or consequence!), without implications concerning spatial or temporal containment. Most importantly, in many cases this relation of functional belonging with is not transitive. For example, (i) through (iii) in the following do not entail (iv):

(i) Changing diapers is part of preserving your baby’s health. (ii) Opening the box with wipes is part of changing diapers. (iii) Pressing your thumb upwards is

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24 For an overview of classical systems see Simons (1987).
25 All taken from the web. Note that ‘is part of’ gets 204 million hits on google, while ‘is a part of’ yields a meagre 11.8 million. For details on GPM compare Selib (2004b, ch.5).
part of opening the box with wipes. *(iv) Pressing your thumb upwards is part of preserving the baby’s health.

Thus the sense of ‘is part of,’ the most frequent type of our common-sense mereological reasons is not adequately captured by the transitive relation ‘<’ as axiomatized within classical mereology. In GPM I offer an alternative axiomatization based on the irreflexive, non-transitive relation ‘C’ (read: ‘is part of,’ ‘belongs with’). In GPM the relationship ‘is part of’ is taken to be the most generic mereological relation and is subsequently further specified into spatiotemporal part, spatial part, temporal part, material part, and a number of varieties of functional part, as sketched below.

3.2 Mereology with partition levels

Since ‘C’ is non-transitive, GPM-parthood reaches only into the immediate or ‘first-level’ parts of an entity. This has immediate consequences for the significance of the irreflexivity of ‘C’:

(Ax1) ¬(xC x)

Since ‘C’ is not transitive, (Ax1) allows for the cease that a whole α makes a functional contribution to one of its own parts β—the whole α cannot be part of itself, but it may well be part of a part of itself.

The non-transitivity of ‘C’ makes it possible to express mereological relationships in a much more differentiated fashion, namely, relative to partition levels.

To introduce the notion of a partition and a partition level, we first define parthood resulting from the n-th iteration of ‘C’:

(D1a) xCn y ↔ for all n in an ordered sequence of natural numbers of length N:
if n = 1 then xC1 n y ↔ xC y;
if n > 1 then xCn y ↔ ∃z(xCz & zCn-1 y)

The relation ‘x Cn y,’ read ‘x is n-part of y,’ indicates the level of mereological embedding of one process in another, but is always relative to a given partition. For example, in Fig. 2 process λ is a 3-part of α and a 2-part of γ. The n-parts of an entity α are those entities y for which ‘y Cn α’ holds, relative to a given partition:

(D1b) x is n-part of y = d(xCn y).

We can take the transitive closure over a sequence of length N of iterated applications of ‘C,’ to define a part-relation that is transitive across partition levels up to the N-th level of the partition:

26 Not all partitions are finite; the identities of nodes of infinite partitions can be preserved by means of GPM’s relativized identity axioms, see below (Ax3a).
Fig. 2 Partition of process α with three levels

\[(D1c) \ x \in \mathcal{N} y \iff x \subseteq y \forall n, 1 < n \leq N, \exists z(x \in \mathcal{N}_n z \& z \subseteq y)\]

For a given entity α, any entity y in the domain of the relation 'y \subseteq \mathcal{N} α' belongs to the so-called N-partition of α. In contrast, any entity y in the domain of '\gamma \subseteq \mathcal{N} α' (the n-th iteration of '\subseteq') belongs to the so-called partition-at-level-n of α. That is, the N-partition of α comprises entities at all partition levels up to and including level m, where m is the last member of N, while the partition-at-level-n of α denotes entities at one level only. Processes at any or all partition levels of a process α below or above a certain 'threshold' can be easily referred to by quantifying over the k-parts of α (in a given partition), where k ≤ n, or k ≥ n. For example, the '≥2-parts' of α in Fig. 2 are ε, θ, λ, κ, and the '≤2-parts' are β and γ.

Fundamental mereological relationships among processes can mainly be stated in terms of 'relative' partition levels, i.e., in terms of partition levels relative to a node in a given partition. For more specific relationships the difference between absolute and relative partition levels become relevant: the absolute partition level is the level determined by one uppermost node of the partition, written 'n(0)'. For example, in Fig. 2 process θ is at the partition level 3 of α (the absolute partition level) and at the partition level 2 of β (relative partition level).

The distinction between relative and absolute partition level also matters for a proper understanding of the anti-symmetry of the part-relation '\subseteq':

\[(A2x) x \subseteq_n y \land y \subseteq_n z \land \neg \neg (x \subseteq y) \iff (\neg (y \subseteq x))\]

(A2x) says that if x and y are at the same absolute level of the partition that has z as an uppermost node, then they cannot be part of each other. This does not exclude infinite partitions, however, where α \subseteq_n β and β \subseteq_n α, i.e., α and β may contain each other at any relative partition level.

Such mutual contains are possible since identity in GPM is defined in relation to a partition level, with the following two axiom schemas, as identity at a level n (see A3a) and identity relative to partition levels up to depth n, (see A3b, where 'G ≤ n' is used to abbreviate the restricted quantification over partition levels, read 'for each m ≤ n'):

\[\neg \neg \text{One of the main tasks of GPT is to investigate how absolute partition levels map into relative partition levels—i.e., how much of the mereological structure of a process is preserved once it becomes part of another.}\]
\[(Ax3a) \forall z (z \subseteq_n x \iff z \subseteq_n y) \iff x =_n y.\]
\[(Ax3b) \forall z (z \subseteq_{\leq_b} x \iff z \subseteq_{\leq_b} y) \iff x =_{\leq_b} y.\]

Two terms are coreferential (in common ontological parlance: ‘two entities are identical’) if and only if they have the same \(n\)-parts or \(\leq n\)-parts. These two identity principles account for the context-relativity of our judgments of sameness; in some contexts coarse-grained comparisons suffice, while others require an in-depth investigation. In this way GPM can be used to reconstruct the insights on either side of the various debates about ‘extensional’ versus ‘intensional’ identity conditions of events.\(^{28}\)

The new technical devices of \textit{parthood at level }\(n\), \textit{parthood up to level }\(n\) and the relativizations of the identity relation afforded by them have many fruitful applications for the traditional problems of ontology (material constitution, persistence and change, individuation of events and actions).\(^{29}\)

3.3 The ‘shallow sum principle,’ interference, and interference products

The fact that \(\subseteq_n\) is a non-transitive relation makes it possible to introduce various degrees of overlap as well as three forms of ‘non-overlap’ among processes: discreteness reaches only into the first partition level, disjointness expresses non-overlap across levels, and divergence establishes non-overlap at a certain partition level. The supplementation principle in GPM is defined in terms of discreteness (symbol: ‘\(f\)’) rather than disjointness or divergence:

\[(A4) x \subseteq y \rightarrow \exists z (x \cap y \subseteq_n z).\]

This allows for wholes to have ‘non-overlapping yet entangled parts,’ i.e., parts at partition level \(1\) that do not overlap at level \(2\) but may share parts, even all of them, at some partition levels below the second level. Mereological product and sum are defined in the usual way, with ‘\(o\)’ for overlap:

\[(D2) \text{prod}(x, y) = \text{at}(z (\forall w (w \subseteq x \land w \subseteq y) \iff w \subseteq z))\]
\[(D3) \text{sum}(x, y) = \text{at}(z (w (w \circ z \iff w \circ x \lor w \circ y)))\]

But due to the non-transitivity of \(\subseteq_n\), the product and sum remain mereologically ‘shallow’ conditions, i.e., they reach only in the first partition level. This has the important consequence that one can use mereological sums in order to distinguish between mere collections and combinations of processes. Any arbitrary sum of general processes may be formed and any sum of general processes is itself a general process, without any implications of spatiotemporal, functional, or causal connections among

\(^{28}\) Since \((Ax3a,b)\) are versions of the classical Proper Part Principle, GPM is a so-called ‘extensional mereology,’ even though the notion of parthood is ‘intensional’ (i.e., not the classical notion of an extent-part drawn from geometric intuitions). Special mapping principles between partitions ensure the identity and diversity of the ‘atoms’ of a partition (or sub-partition, respectively).


\(^{30}\) \(\subseteq_n\) is defined as ‘is part of or identical to.’
the parts of a sum—sums are mere collections of processes, and since ‘is part of’ does not imply spatial or temporal inclusion, sums of processes may be arbitrarily scattered in space and time.

However, for many sums of processes that matter in our theory formation it holds that the processes involved interact. We shall turn to the specifics of interactions presently in the next section, but there is a general description of interaction that straightforwardly can be put in place with the resources of GPM. Generally speaking, when processes interact they ‘interfere’ with one another in some fashion, thus changing the make-up of the complex process. Consider Fig. 3, where $\gamma$ is the sum of $\alpha$ and $\beta$, and $\omega$ is the sum of $n > 1$-parts of $\alpha$ and $\beta$ plus an additional process $\eta$, which does not occur anywhere in the partition of $\alpha$ nor of $\beta$.

In general we can define an interference as any mero logical structure where, intuitively speaking, the parts below the first level participate in a new complex dynamics. More precisely, let $1 < n, m \leq q$, where $q$ is the maximum of $N$ and $M$ (which are the number of levels in the partitions of $x$ and $y$, respectively), and $n$ may be equal to $m$:

$$(D4) \text{Int}(x, y) \leftrightarrow (\exists \forall v_i, v_j (z = \text{sum}(v_i, v_j) \rightarrow (v_i \subseteq x \lor v_j \subseteq y)) \land \exists v_k (v_k \subseteq z \land \neg (v_k \subseteq x \lor v_k \subseteq y))).$$

According to this definition two processes interfere if some of their $n$-parts occur in a sum (called the ‘interference focus,’ with the associated predicate ‘Int-foc($x$, $y$, $z$)’)) that has as part a feature not contained anywhere in any of the partitions of the component processes; that feature is called the ‘interference product,’ with the associated predicate ‘Inter-prod ($x$, $y$, $z$, $v_k$)’.

As it stands, (D4) holds for many processes, since the sum operation is unrestricted and the disjointness condition for the interference product is easily fulfilled. The primary function of the predicate ‘Int($x$, $y$)’ is to highlight a mero logical structure for further specification. As shall be sketched presently, by adding further conditions on
the parts that enter into the interference focus or on the interference product we can get closer to, and further diversify, the common notion of interaction as involving mutual causal effects.

3.4 Spatiotemporal location, amounts, and quantities

All general processes are concrete in the sense of being spatiotemporally located. But spatiotemporal location itself is an interference in GPT—the locating of a dynamics \( \alpha \) is the interference focus \( \rho \) of the interference of the dynamics spacetime, denoted by the constant ‘R,’ and \( \alpha \).

\( (A5a) \) General Location Postulate: \( \forall x \text{Int}(x, R) \)

The interference focus \( \rho \) of \( \text{Int}(\alpha, R) \) has a unique interference product:

\( (A5b) \) Specific Location Postulate: \( \forall x \exists y (y=\text{focus}(R, x) \land \exists w (\text{Int-prod}(R, x, y, w))) \)

The unique interference product of a locating is a dynamics that is, intuitively speaking, a specification of the dynamics that is being located, i.e., \( \alpha \)-as-it-occurs-in-spatiotemporal-region \( r \). Any such location-specific dynamics is a dynamics in its own right—snowing on Mount Everest, for example, is a different sort of snowing than the snowing at the Danish coast; photosynthesis in this plant differs slightly from all others, already due to different angles of illumination; metabolism in you differs from metabolism in me; etc. Any location-specification of a dynamics \( \alpha \) is called being an amount of \( \alpha \) in region \( r \) and abbreviated \( '\{\alpha\}' \).

\( (D5) x = [y], \Leftrightarrow \exists z (z = \text{Int-focus}(R, y) \land x = iw \text{Int-prod}(R, y, z, w)) \)

While Leibniz postulated that concrete individuals, (e.g., this leaf) are ultimately specific kinds (ultima species) in the sense of (a) distinct from all other instances of their kind and (b) ‘fully determinate’ with respect to all possible predications, GPT operates with only the first assumption: an amount of a dynamics \( \alpha \) is sufficiently determinate to ensure its distinctness from other amounts of \( \alpha \), but it may otherwise remain more or less indeterminate. The idea of admitting indeterminate (‘generic’ or ‘schematic’) concrete individuals goes directly against the orthodoxy of the ontological tradition—the presupposition that concreteness entails determinateness—but apart from the ‘narrative force’ of the ‘myth of substance’ mentioned above there is no law of thought prohibiting such a move.

Furthermore, since GPT also renounces the postulate that all concrete individuals are particulars (i.e., location individuated entities), we receive a much richer conception of situatedness. In GPT there are three types of situatedness. The first of these is trivially fulfilled, via the general location axiom: a dynamics is indefinitely located iff it interferes with the dynamics of spacetime; this is the type of situatedness that

\( ^{31} \) The GPT-account of location combines most straightforwardly with an entitative (commonly called “substantivalist”) conception of spacetime; note that it is assumed in GPT that absolute vacua are impossible.
can be ascribed to non-countable, non-particular items as denoted, for example, by the subject terms of generic sentences ‘chemiosmosis is part of photosynthesis’ or ‘water freezes around 32F.’ Second, a dynamics α is definitely located in a place s (interval t) iff there is an amount of α in a spatiotemporal region r associated with s (or t, respectively);32 this is the situatedness typical of countable items as denoted, for example, by the expressions ‘my cat,’ ‘the sample on dish 231,’ ‘the football game this Saturday,’ ‘moved 1 meter between t₁ and t₂;’ or ‘is collapsing.’ Third, a dynamics α is indefinitely located in a bounded region r iff α is quantity q of β and there is a measurement process γ on [γ]ₖ which yields an amount [β]ₖ associated with q.33 This is the type of situatedness that we assign to countable entities that are not uniquely located (i.e., non-particular); such entities we speak about in sentences about contained quantities, such as ‘the 1 dl gin in this 3 dl gin-and-tonic is hardly to be noticed’ or ‘this probe contains at least 3 mg manganese.’34

3.5 Parameters for a typology of general processes

As it appears, the parameters of five evaluative dimensions suffice to generate a rich classificatory matrix for general processes or dynamics. The first dimension specifies the homometry and automerity pattern of the dynamics as outlined in Section 2.5 above, i.e., the characteristic spatial and temporal occurrence (recurrence) patterns of the dynamics. The second dimension, participant structure, differentiates dynamics with respect to number and type of causal agents and patients. The third dimension contrasts basic varieties of dynamic constitution or process architecture, such as sequences, forks, joints, cycles etc. The fourth dimension, dynamic shape, classifies dynamics according to their typical (part of) trajectories in phase space, some of which correspond with distinctions familiar from linguistic theories of “Aktionsarten” and verbal aspects (telic/atelic, ingressive, egressive, repetitive, conative etc.). The fifth dimension, dynamic context, classifies a dynamics (e.g., a biological organism) relative to its influence on the generative environment (e.g., the organism’s ecosystem) of the process.

In sum, according to the theory of general processes, the world is “the ongoing tissue of goings-on”35—the entities of any domain of a language or theory are best described as general processes, i.e., as individuals which are (i) concrete or spatiotemporally occurring but do not necessarily occur in a determinate bounded region, (ii) more or less specific or determinate, (iii) more or less spatially and/or temporally

32 The association of places or intervals with spatiotemporal regions is relative to context; ‘in Mexico City’ denotes different spatial regions for the geographer and the sociologist.
33 Since quantities are the results of measurement interactions, the definition of the predicate ‘x is a quantity of y’ is complex and will be omitted here. In first approximation, a quantity q of x (where q consists of numerical value n, a measure M, and a measurement dimension, e.g., 3 dl of water, 5 g, 15 A), is that within a region r which a generic measurement process could causally interact with to yield an amount of x (frequently located outside of r) that has the causal features measured in terms of q. Note that the expression ‘[β]ₖ’ is shorthand for an existential quantification, ‘some amount of β.’
34 Perhaps this is also the type of situatedness of field quanta, see Seibt (2002) and Seibt (2004b, ch.5).
recurring, and (iv) more or less complex. Such complexity, as we will see presently, derives from the interaction of processes. Endorsing Aristotle’s intuition that being and individuality are conceptually inseparable, i.e., that whatever there is (for us) is distinct from something else, GPT aims to show that this intuition is best developed if we—pace the ontological tradition—insist on keeping individuality conceptually separate from particularity (necessary unique locatedness). According to GPT, whatever we talk about in common sense and science is an individual the distinctness of which does not derive from its unique placement (which it may but need not have) but from ‘what it does’ or ‘how it interacts,’ i.e., from its mereological relationships to other processes. An amusing illustration of the ‘general spirit’ of GPT-interpretations can be found in Quine’s playful remark that process ontologists read the sentence “a white cat faces a dog and bristles” as “it’s cattin whitely, bristlingly, and dogwardly.”

4 Some forms of emergence interaction in GPT

As mentioned above, all general processes interfere with each other—the predicate of interference is almost trivially fulfilled. However, by imposing further conditions on the parts of the interference focus and the interference product, the field of interfering general processes can be sorted further into those that ‘genuinely interact’ and ‘combine’ in various senses of these terms. For present purposes I will focus on sketching definitions for those forms of interaction that figure centrally in ‘interactivist’ approaches.

4.1 Two preliminaries

As mentioned above, the locating of a dynamics α is itself a dynamics ρ, an interference that has as interference product a specific variety of that dynamics (called ‘amount of α in r,’ abbreviated ‘[α]r’), and it is part of the latter that it extends a spatiotemporal region r. The spatiotemporal (spatial, temporal) subregions s₁,...,n of r determine the spatiotemporal (spatial, temporal) parts of [α]r. These may or may not be amounts of α themselves—for example, if α is an activity-like process such as melting, the temporal parts of [α]r will be amounts of α, i.e., [α]ₜ₀, and if α is a development-like process such as breaking apart with dissimilar stages then the temporal parts of [α]r will be amounts of those dynamics that are parts (simpliciter!) of α, i.e., [x]ₜ₀ in case x¢α. Two amounts of dynamics spatiotemporally (spatially/temporally) overlap in region r iff they have a spatiotemporal (spatial/temporal) proper or improper part that extends r.

As a second preliminary remark, let me highlight some basic distinctions in occurrence types. Inspired by Aristotle’s distinction between “complete” and “incomplete” actions, philosophers and linguists have long been discussing suitable classifications of

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36 Cf. Quine (1985, p. 169). I owe the pointer to this illustration to L.B. Putnam.

37 That amounts of dynamics ‘extend spatiotemporal regions’ is a metaphor to be cashed in. Whitehead’s construction of the ‘coordinate division’ might be the obvious place to turn to for inspiration.

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types of occurrences denoted by sentences with verbal predications. As adumbrated above, in GPT a basic distinction is drawn between ‘activity-like’ processes (or briefly, ‘activities’) such as burning or snowing, which are temporally maximally like-parted and self-parted (homenerous and automerous), and ‘developments’ or ‘events,’ such as exploding or embryonic ontogenesis which are temporally minimally like-parted and self-parted—each temporal part is a ‘stage’ in the process. Proper developments with internal structural differentiation can be set apart from ‘bounded activities,’ such as swimming to the glucose source or emitting heat for 5 s, which are ‘monotonous’ in occurrence, i.e., temporally almost maximally like-parted apart from the goings-on at the boundaries. Statements about ‘results’ (in Vendler’s terminology ‘achievements’ and ‘states’) such as A wins the race or A has velocity v at t, do not denote occurrences of a separate type but redscribe developments or bounded activities (e.g., crossing the finish line or moves from p₁ to p₂ in interval I) relative to an encompassing functional context.

4.2 Two basic varieties of interaction

Let us now take a closer look at the notion of interaction. In general, an interaction in GPT is an interference with unique interference focus, i.e., of the many sums of n-parts of x and m-parts of y that fulfill the definiens of ‘Int (x,y),’ the GPT-predicate ‘Interact(x, y)’ denotes exactly one such sum. According to our common understanding of the term, an interaction has two features: first, the interacting dynamics overlap spatiotemporally, and, second, the interacting dynamics change each other mutually. This latter feature of the mutuality of change can be taken in two different ways. On the one hand, it can be taken as sequence of ‘changes back and forth,’ the one affecting the other and vice versa. Such ‘sequential interactions’ can be rendered more precise as follows:

(D6: Sequential interaction): An interference of x and y is a sequential interaction if x and y spatiotemporally overlap in t, and the interference focus [z]ₜ has the temporal homomerity and automerity profile of a series of developments, and there are at least two interference products that do not exactly overlap temporally (i.e., are not co-occurrent).

38 Cf. Aristotle Metaphysics 1048b18-b35; while philosophers initiated the contemporary debate about occurrence types as a question about the meaning of action verbs, cf. e.g. Vendler (1957), since the late 1970s this research track has been taken up by linguists, with Mourelatos (1978) providing the seminal interdisciplinary interface, and connected to the study of linguistic ‘Aktionsarten’ and verbal aspect. For a discussion of current linguistic analyses of verbal predicates see Selib (2004a) and, in particular, Selib (2004b, ch. 2).

39 I am omitting here some finer points: even though the stages of a development are unlike the whole (which is thus minimally like-parted and self-parted), developments might be further distinguished in terms of their ‘relative internal homogeneity,’ i.e., in terms of whether some of their stages are like each other.

40 For reasons of expositional simplicity, interaction is here treated as a 2-place predicate, but of course it can have many arguments.
The prime examples for such sequential interactions are chain reactions in chemistry,\textsuperscript{41} but they may also be realized by entangled feedback loops. On the other hand, the mutuality of interaction may be gauged from the result of its occurrence rather than associated with stages of a development. In this case interaction is taken as a ‘homogenous and holistic’ dynamics that co-occurrently affects both interactants. To render this reading of ‘simultaneous interaction’ more precise, we can offer in GPT the following:

\textbf{(D7: Co-occurrent interaction):} An interference of x and y is a co-occurrent interaction if x and y spatiotemporally overlap in r, and the interference focus \([z]_r\) has the temporal homomery and automeity profile of a monotonous development or of a bounded activity, and there are two co-occurrent interference products \([v]_r\) and \([w]_r\), which amount to changes in n-parts of x and m-parts of y, respectively.

As it stands, this characterization of co-occurrent interactions does not require that the interference products \([v]_r\) and \([w]_r\)—which represent the ‘double effect’ of the interaction on each interactant—are in some fashion ‘correlated.’

4.3 Causal interaction and causal connection

Consider again the definition of co-occurrent interaction in (D7). If we additionally assume that \([v]_r\) and \([w]_r\) represent changes in n-parts of x and m-parts of y, respectively, that amount to the “exchange of a conserved quantity” (e.g., momentum), we find that co-occurrent interaction has its prime example in causal interaction as defined in W. Salmon’s process theory of causation. In Salmon’s formulation, “a causal interaction is an intersection of world-lines that involves exchange of a conserved quantity ...”\textsuperscript{42} The GPT-version of causal interactions is accordingly:

\textbf{(D8: Causal interaction):} An interference of x and y is a causal interaction in region r iff x and y interact co-occurrently, and there are quantities \(q_x\) and \(q_y\) which are n-parts of x and y, respectively, and the interference products \([v]_r\) and \([w]_r\) (where \(r_1\) and \(r_2\) are overlapping subregions of r) are developments changing \(q_x\) into \(q_{x-k}\) and \(q_y\) into \(q_{y+k}\).\textsuperscript{43}

\textsuperscript{41} Such as transition metal alkene metathesis, the focus of the nobel-prize in chemistry in 2005. As described by J.-L. Hétizon, J.-L. and Y. Chauvin in 1970, in this reaction first an alkene double bond is generated by a cycloaddition of two alkenes, which together with the metal catalyst yields a transition metal alkyldene, which then forms a metalloctylobutane intermediate that cycloreact to give either the original or a new species of alkene and alkyldene.


\textsuperscript{43} Read ‘k’ as ‘k ± Δk’ to account for dissipation. Recall that contained quantities in GPT are entities in their own right—they are represented by numerical values of a unit of a measuring dimension but are in themselves individuals that are indeterminately located in a bounded spatial region r occupied by some stuff \([x]_r\) containing the quantity (example: this bottle, i.e., the amount of water in this bottle, contains 3 dl water). Changes in quantity q of a stuff-like process x are frequently but not always connected with spatial movements of x; note, however, that in GPT it is also possible for quantities themselves to move—they are, after all, concrete like amounts of stuff and merely have a different form of situatedness by being indeterminately located. This saves (D8) from the difficulty arising for the Salmon/Dowele account.
We can then follow Salmon’s general strategy and use the notion of a causal interaction to define causal processes:

A process transmits a conserved quantity between A and B \((A \neq B)\) if and only if it possesses [a fixed amount of] this quantity at A and at B and at every stage of the process between A and B without any interactions in the open interval \((A, B)\) that involve an exchange of that particular conserved quantity. \((\ldots)\) A causal process is the world-line of an object that transmits a non-zero amount of a conserved quantity at each moment of its history (each spacetime point of its trajectory). \(^{44}\)

But here the GPT-idiom allows for a shorter version:

\((D9: \text{Causal Process}):\) A dynamics \([\alpha]\) is a causal process iff a conserved quantity \(\beta\) is part of \(\alpha\) and \(\alpha\) is temporally maximally automorous.\(^{45}\)

If \(\alpha\) is temporally maximally automorous, its parts—including \(\beta\)—exist in all sub-regions of an amount of \(\alpha\), which excludes the undesired possibility that the quantity \(\beta\) is the result of a development produced by a causal interaction with \(\alpha\). Since causal processes as defined in \((D9)\) are not ‘telic,’ i.e., are not developments with a culmination point, one might wonder in which sense they can be said to be ‘directed,’ ‘transmitting’ or ‘propagating’ something. In GPT these metaphors can be spelled out to some extent by specifying the spatial regions in which the dynamics \([\alpha]\) successively occurs.\(^{46}\) Moreover, since causal processes are ‘activity-like’ temporally automorous processes, they are not ‘productive’ in the common sense—‘causal production’ is always due to a causal interaction as defined in \((D8)\).

However, frequently when we talk about causal interactions—for instance, in statements about causal interactions between molecules or organisms—we do not intend directly to make reference to conserved quantities (charge, mass/energy, momentum). Thus it is useful to introduce an additional predicate to capture a more generalized sense of causal connection in the sense of a ‘causally based interaction’:

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Footnote 43 continued
namely, that the exchanges of quantities mentioned in the definition of a causal interaction—i.e., essentially exchanges of mass/energy, charge, and momentum—would seem to be itself based on more fundamental causal interactions.

\(^{44}\) Salmon (1997, pp. 462, 468).

\(^{45}\) Again, according to the ‘initiative’ reading of quantity adopted in GPT, a given beam of light, for example, is a certain quantity of electromagnetic energy as much as it is an amount of illuminating-area-A—thus inversely, both are part of what it is to be that beam of light.

\(^{46}\) Note that ‘dynamically,’ which is a feature attributed to all individuals of GPT, i.e., postulated to hold for any relatum of \(\langle C, \ldots\rangle\), is mereologically defined, yielding only the weak sense of ‘directedness’ involved in self-realization, not the strong sense of ‘propagation.’
(D10: Causal connection): dynamics \([x]\) is causally connected to dynamics \([y]\) iff there is a spatiotemporal \(n\)-part \([x_i]\) of \([x]\) that causally interacts with a spatiotemporal \(m\)-part \([y_j]\) of \([y]\).\(^{47}\)

4.4 Mechanistic interaction

The GPT-definitions I have set out so far can be usefully applied to insert oneself into the recent debate about the definition of a mechanism. Here is an example of the target phenomenon that descriptions of mechanisms are supposed to capture: the first phase in photosynthesis, the transformation of light energy into chemical energy that takes place in the thylakoids of chloroplast.

Photons are absorbed by pigment molecules in large complexes. . . . The absorption of this light energy excites electrons [in these complexes], which are then picked up by the electron transport chain. As the electrons are transported down the chain, released energy is used to pump hydrogen ions across the thylakoid membrane creating a positive charge within the thylakoid, and thereby producing a proton motive force. As these protons pass back across the thylakoid membrane by osmosis, chemical energy in the form of ATP is generated by ATP synthetase.\(^{48}\)

The first step in trying to come to grips with such a phenomenon would seem to consist in determining the dynamic categories of the occurrences involved, just as one might begin a description of a box full of things by determining which kinds of things they are. But participants in the debate about mechanisms pass over this first step of analysis and use the notions ‘change,’ ‘activity,’ ‘process,’ ‘dynamic process,’ ‘interaction,’ ‘exchange’ in ways that partly go against the categorial meaning of these terms as worked out by linguists and ontologists during the last decades. For example, Machamer, Darden, and Craver define mechanisms as “entities and activities organized such that they are productive of regular changes from start or set-up to finish or termination conditions” and the inclusion of “activities next to entities”—i.e., the things that engage in these activities—is justified by the fact that “activities are the producers of change.”\(^{49}\) This usage of ‘activity’ blurs the important distinction between activities and developments, between—in the linguistic idiom—‘a-telic’ and ‘telic’ occurrences, or better, following the spirit of Aristotle’s original distinction, ‘endo-telic’ and ‘exo-telic’ occurrences, of which only the latter are productive.\(^{50}\) In

\(^{47}\) The numbers \(n\) and \(m\) refer to partition levels in the N-partition of \([x]\) and the M-partition of \([y]\), respectively. The two-place predicate ‘\(x\) is causally connected to \(y\)’ can be extended to an \(n\)-place predicate, see below.

\(^{48}\) Cf. Tabery (2004, 4f).

\(^{49}\) Machamer et al. (2000, 4f).

\(^{50}\) The contrast between ‘a-telic’ and ‘telic’ occurrences common in the linguistic discussion of Aktionsarten is an unhappily vague and allusive modification of the Aristotelian claim that activities (“seeing”) have their telos within themselves and thus are at every moment complete, while developments (“building-a-house”) are incomplete since their telos is outside of the occurrence of the development in the product they bring about.
the view of Machamer et al. ‘activities’ are “types of causes” as for example denoted by the verbs “scrape, push, dry, carry, eat, burn, knock over”—but these are verbs that linguistic/ontological accounts of occurrence types classify as ‘activity verbs’ (‘scrape,’ ‘push,’ ‘carry’) or as ‘accomplishment/development verbs’ (‘knock over’) or verbs that can be given both an activity reading or a reading as an accomplishment (development) with completion point or product (namely, ‘dry,’ ‘burn,’ ‘eat’).

Critics of Machamer et al. have been similarly oblivious of the distinction between ‘endo-telic’ and ‘exo-telic’ occurrences, between ‘activities’ proper and developments, pointing out that “pumping [of electrons] can create a motive force but this activity is only productive when it is embedded in a particular mechanism” which requires mentioning of the specific property changes produced.51 The problem noticed by Machamer’s critics is that a definition of a mechanism should combine three basic ideas: (a) a mechanism is a sequence of changes; (b) these changes are regular; (c) the notion of a mechanisms is tied up with the idioms of ‘productivity.’ However, the conceptual resources used by Machamer’s critics also do not suffice to express these three basic ideas sufficiently well. The most recent suggestion has been to combine the notion of an ‘activity’—understood as a general placeholder for something ‘dynamic’—with a pair of transition states specifying the properties it begins and ends with.52 But on this strategy it remains unclear how such transitory ‘activities’ are related to the states they connect, and how the feature of productivity—which, as just quoted, ‘activities’ are said to lack in themselves—derives from this relation.

It is preferable, I believe, to distinguish clearly between characterizations of dynamics implying productivity (i.e., developments) and those which are not (activities). Often the ‘intermediate occurrences’ in a mechanism seem to exhibit, from a coarse-grained perspective, the typical uniformity of ‘activities’ or temporally autotermous dynamics. For instance, thermal rotation around the carbon–carbon double bond in nitroenamines, chemiosmosis in photosynthesis, or the oscillating pawl in a ratchet mechanism seem to be homogenous rather than developmental dynamics. At a closer look, however, these dynamics are (complexes of) sequences of developments (which it may not be relevant to identify at the given level of description, or which may not yet be understood). Machamer et al. recommend their notion of ‘activities’ as a response to the difficulty that while “Salmon’s analysis may be all there is to certain fundamental types of interactions in physics, his analysis is silent as to the character of the productivity in the activities investigated by many other sciences.”53 However, in my view Machamer’s et al. strategy of assigning causal productivity to ‘activities’ creates more conceptual problems than it solves.

To find a suitable alternative strategy, let us distinguish three intuitions that motivate Machamer et al.’s inclusion of “activities”: (a) mechanisms are something “dynamic” and thus mere descriptions as regular sequences of states will not suffice; (b) causal interactions are ‘productive’ in the sense that they bring about a ‘new’ (qualitatively

51 Tabery (2004, p.11). As examples of ‘activities’ Tabery again uses both verbs that from the linguist/ontologist’s point of view are activity verbs: “transporting,” “pushing,” but also ‘accomplishment verbs’ or verbs for developments: “binding,” “breaking.”

52 This is Tabery’s suggestion, cf. Tabery (2004).

53 Machamer et al. (2000, p.7).
different) state of affairs; and (c) "fundamental types of interactions" involving the exchange of conserved quantities in physics are part of more complex, uniform (thus somewhat 'activity-like') dynamics that other sciences focus on when they identify causal connections. The conceptual tools of GPT enable us to articulate these three intuitions in a different and more precise fashion. (a) Mechanisms are a dynamics like everything else in GPT. (b) As defined in (D8), causal interactions are developments and thus suitable candidates for being 'productive.' (c) Mechanisms involve causal interactions, but mainly are described in terms of causal connections. As defined in (D10), causal connections are (complex of) sequences of developments, which may or may not be 'productive' in the sense of bringing about a new condition or state of affairs. For example, the 'pumping' and 'exciting' mentioned in the above description of photosynthesis are productive, while the maintenance of certain conditions, such an oscillatory movement that merely keeps an item available for further interaction, is not. The hallmark of a mechanism is, however, that there is at least one chain of productive causal connections between initial and final dynamics.

To explain the characteristics of this chain, consider the following GPT-account of the first steps of photosynthesis, following closely the description quoted above. Let \( \phi \) in the following be a variable for a collection (sum) of spatiotemporal regions \( s_i \) that temporally overlap, are all located in the 'container region' \( r \) (the location of a piece of chloroplast), but are possibly spatially disconnected; \( \psi \) is thus in effect a variable for a multiplicity of locations in \( r \). The complex dynamics \( \alpha \) of \([\text{being-a-photon}]_\psi \) (i.e., a certain multiply located amount of \text{being-a-photon}, which is the GPT-term for 'being a group of photons in the same spatial region at interval \( T \)') interferes with the dynamics \( \beta \) of \([\text{being-a-pigment-molecule}]_\psi \). The focus of this interfering is the dynamics \( \gamma \), an amount of a specific type of absorption \([\text{absorption}]_\psi \), which is a causal connection between \( \alpha \) and \( \beta \), i.e., \( \text{Int-foc}(\gamma, \alpha, \beta) \) and \( \gamma = CC(\alpha, \beta) \). That electrons in \( \beta \) are getting into an excited state is part of what it is for this type of absorption to occur in \( r \), i.e., \( \delta \), the dynamics of \([\text{exciting-electrons}]_\psi \) is part of \( \gamma \) but neither \( \phi \)-part of \( \alpha \) nor \( \psi \)-part of \( \beta \), respectively, and thus \( \delta \) is the interference product of \( \gamma \) \( \text{Int-prod}(\delta, \gamma, \alpha, \beta) \). The dynamics \( \delta \) interferes with the dynamics \( \epsilon \) of \([\text{being-an-electron-transport-chain}]_\psi \), and the focus of this interference is the causal connection \( \zeta \), the dynamics of \([\text{transporting-electrons-down-the-electron-transport-chain}]_\psi \), thus \( \text{Int-foc}(\zeta, \delta, \epsilon) \) and \( \zeta = CC(\delta, \epsilon) \), and \( \zeta \) has as interference product the dynamics \( \eta \) of \([\text{being-a-quantity-of-energy}]_\psi \), \( \text{Int-prod}(\eta, \zeta, \delta, \epsilon) \). The dynamics \( \eta \) that represents this quantity of energy interferes with the dynamics \( \theta \) of \([\text{being-a-hydrogen-ion}]_\psi \) in a dynamics \( \iota \) that is located in a region beyond \( r \) and is metaphorically described as \([\text{pumping-hydrogen-ions-across-the-thylakoid-membrane}]_\psi \), \( \text{Int-foc}(\iota, \eta, \theta) \), Part of \( \iota \) (but not of \( \eta \) or \( \theta \)) is \( \kappa \), the dynamics of \([\text{being-a-moving-proton}]_\psi \), i.e., \( \text{Int-prod}(\kappa, \iota, \eta, \theta) \), etc.

Despite some questionable simplifications in the description of the dynamics involved here, the example can, I trust, illustrate the general structure of mechanistic interaction, namely, as a chain of interference foci such that each interference focus causally connects the dynamics it interferes, and has as interference product a dynamics that is part of a further interference focus of this kind. The general structure of this complex dynamics of process chaining can be stated in a simplified fashion as follows,
contracting ‘int-foc’ and ‘CC’ into the predicate of ‘causal interference’ and adding
the interference product as the third place:

(S1: Dynamic schema of mechanistic interaction between stages of a development)

\[ \ldots s_n = \text{causal interference (y, z, v)} \]
\[ s_{n+1} = \text{causal interference (v, u, t)} \ldots \]

Formulating this pattern more precisely we receive:

(D11) A dynamics x is a mechanism iff x has the homomery and automtery
pattern of a regular development; and dynamics \( y_1, \ldots, n \) are the stages of x; and for
each stage \( y_i \), with \( 1 < i < n \):

\[ \forall z, w, v, u \ (x \subseteq y_{i-1} \wedge w \subseteq y_{i-1} \wedge \text{Int-foc}(y_i, z, w)) \wedge \text{CC}(y_i, z, w) \wedge \text{Int-prod}
(v, y_i, z, w) \rightarrow \exists u \ (u \subseteq y_{i+1} \wedge \text{Int-foc}(y_{i+1}, v, u) \wedge \text{CC}(y_{i+1}, v, u)) \]

A regular development is in GPT defined as a development with a fixed sequence of
stages—each amount of such a development has the same kind of stages in the same
order. This suffices to account for the regular proceeding that we commonly connect
with the idea of a mechanism and a ‘mechanic’ course of events. For note that the rela
tional predicate ‘is part of’ already expresses regular relationships between dynamics.
If the dynamics mentioned have the degree of generality that is typical for our talk
about mechanisms (cf. ‘in dipolarization sodium moves into the cell by diffusion and
electrical attraction’) the part-relationships in (D11) express the kind of regularity that
elsewhere the notion of a “direct, invariant, change-relating generalization” is sup
posed to capture.\(^{54}\) Based on (D11) we can introduce the predicate ‘mech-int(x, y, z),
stating that mechanical interaction is the interaction that connects the initial stage y
of mechanism x with its final stage z.

4.5 Functional interactions

The GPT-formalism can also be employed to distinguish between three notions of
functions. We sometimes use the term ‘function’ to denote an entity’s typical ‘activity’
(what an X normally ‘does’ or is ‘engaged in’)—e.g., the ‘function’ of the flag
is to blow in the wind, the ‘function’ of gold is to shine. Often this notion of function
is used—as above, cf. Section 2.3—to articulate a contrast to location-based identity
in terms of ‘qualitative’ aspects, and commonly the ‘is part of’ relation is used for
that purpose: feeding, hunting, and giving birth to kittens is part of being a cat. As
this example displays, this vague sense of function as articulating a ‘dynamic role’
consciously blurs distinctions between constitutive dynamic component, characteris
tic activities, and causal consequences of a dynamic. Since the ‘is part of’ relation is
the basic constructive relation in GPT, the axioms of ‘C’ can be taken to model the
vague sense of function as ‘dynamic role,’ as joint engagement (‘belongs with’) or
typicality of behavior.


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Of the more specific senses of function, I want to distinguish here two. First, there is 'functioning' in the sense of something's displaying the behavior it is 'supposed' to display, as regulated by some 'control' system:

When I take a suitcase and prop it against the elevator door, intending to thereby hold the door open, the job of the suitcase is (for the moment) to hold the elevator door open. That is what it is supposed to do. (...) Just as intentional regulation is a common phenomenon in the human world, natural regulation is common to the natural world. There are natural systems regulating the replication of DNA, regulating human body temperature, regulating clutch size in snowy owls, regulating levels of carbon dioxide in the atmosphere, and so on.55

The details of this so-called 'regulation account' of function are missing and one way to supply them would be by describing regulation in terms of process architecture. Regulation in the envisaged sense denotes a relation between two dynamics (systems), which may themselves be components of an encompassing system. The regulating system, an amount of a complex dynamics [α]—e.g., the habitat of the snowy owl considered over an evolutionarily significant temporal interval—has as part a dynamics [β] e.g., the arctic mouse) that causally interferes with a part [γ] e.g., the clutches) of the regulated system [δ] e.g., the snowy owl); this causal interference has as interference product ε a causal mechanism (e.g., the owl's genetic reproduction) with initial stage ψ that produces a dynamics γ' which is another amount of γ (or an amount of a modification of γ). By means of the predicate 'mech-int(x, y, z)' just introduced at the end of Section 4.4, we can then describe regulation schematically as follows:

(S2: dynamic schema of α regulating β at stages $s_n, s_{n+m}$)

- $δ \subseteq α, ε \subseteq α, γ \subseteq β, φ \subseteq ε$
- $s_n = \text{causal interference } (δ, γ, ε)$
- $s_{n+m} = \text{mech-int } (ε, φ, γ')$
- $s_m = γ' \subseteq β \text{ and } ¬γ \subseteq β$

Much is omitted in S2, such as the triggering of the interference at $s_n$ or the scope of the modification effected. What the schema can reveal, however, is that the mere fact of being regulated fails to capture the common normative sense of functionality in the sense of being 'for the sake of something': there is no link between δ, the regulated dynamics, and the outcome of the regulation process γ'. A regulated system does what it is "supposed to do," but the normativity at issue is merely the causal fact that, under certain conditions, some of specific varieties of the occurrences that are its dynamic parts are replaced by others. The system's doing what it is supposed to do here is nothing more than 'displaying a certain type of behavior, i.e., behavior within a certain parameter space determined by the causal mechanisms of the regulating system.'

To gain a stronger sense of functioning as occurrence 'for the sake of' something, one might postulate explicitly an aim or goal of the regulated behavior.56 Alternatively,

56 Cf. Schroeder (2004, p. 120) who in this vein postulates that natural regulations have some "aim or end," thus leaving a purely regulatory account behind.
one might extend the dynamic structure of the regulation and introduce something akin to a positive feedback link from the regulated behavior to itself, or to some dynamics containing it. But it is crucial to distinguish here between ‘self-enhancing’ and ‘kind-enhancing’ regulated behavior. As critics of the etiological account of function have pointed out, causal evolutionary history at best can account for kind (species)-enhancement—the occurrence of the feature (size-S-clutches of snowy owl $O_1$) engenders a causal chain leading to the occurrence of a feature of the same kind (size-S-clutches of snowy owl $O_2$). In GPT-terminology, the etiological account of function operates with positive feedback cycles that connect, per mechanistic interaction, different amounts of the same dynamics.\(^{57}\)

(S3: Dynamic schema of a virtual positive feedback dynamics $\alpha$)
$x$ and $y$ are two amounts of $\beta$, i.e., $x = [\beta]_1, y = [\beta]_{1+n}$
mech-int ($\alpha, x, y$)
$\alpha \subseteq \beta$\(^{58}\)

Virtual positive feedback dynamics ensures the repetition of a kind $\beta$ (typically denoted by generic nouns such as ‘the heartbeat,’ ‘the snowy owl’) by a mechanistic interaction that relates exemplars of the kind (amounts of $\beta$); that this mechanistic interaction is part of what $\beta$ is—i.e., that the evolutionary history of a biological kind is part of what that kind is—represents the core claim of the etiological account of function. Any occurrence of the regulated behavior or feature (e.g., heartbeat in snowy owl $O_1$) contributes to the occurrence of another (heartbeat in $O_1$’s offspring) and is in this sense ‘for the sake of’ or functional for the recurrence of the kind. Note that the fact that a behavior contributes causally to the recurrence of the kind does not, as such, imply anything about the usefulness of the occurring behavior for the biological system in which it occurs.\(^{59}\)

Functionality in a stronger sense, on the other hand, can be attributed to processes that are self-enhancing in the most literal sense. Autocatalytic reactions provide a good example: oxalic acid reacts with permagnate and produces manganese, which in turn acts as a catalyst for the reaction. Schematically this dynamics can be stated as follows.\(^{60}\)

(S4: Dynamic schema of a positive feedback dynamics $\alpha$)
$[\alpha]_1 = \text{causal interference } (x, y, [\beta]_1)$
$[\beta]_1 = \text{causal interference } (v, w, [\alpha]_1)$

\(^{57}\) The definition can be modified to allow for non-causal (e.g., biosomiotic) sequential interactions in the evolutionary history of a biological feature, especially in the phases of genetic reproduction.

\(^{58}\) All dynamics are part of their amounts, thus, $\beta \subseteq [\beta]_1$ and if $[\beta]_1 \subseteq \alpha$, as implied by mech-int ($\alpha, x, y$), it holds that $\beta \subseteq_2 \alpha$. Since the antisymmetry of '$\subseteq$' does not hold across partition levels, we can postulate that $\alpha \subseteq [\beta]$ even if $\beta \subseteq_2 \alpha$.


\(^{60}\) Recall the difference between amounts and quantities in GPT: the quantity of manganese continuously changes in this reaction, but the reaction can be counted as one amount, one concrete occurrence of ‘being-manganese.’
Both the reaction $[\alpha]_r$ and the reaction product-cum-catalyst $[\beta]_r$ are self-enhancing in the sense of contributing causally to the occurrence of `being-\alpha` and `being-\beta` in region r, i.e., to themselves. Thus they are useful for themselves and can be said to implement functionality in its normative sense, while they themselves provide the norm of useful operation—their usefulness or `being for the sake of` thus is not a matter of ascription but is grounded in their own dynamic architecture.

As proponents of interactivism have pointed out, a process may not only enhance (e.g., speed up) the dynamics which it is part of, it may also warrant its continued existence. A so-called “self-maintaining” or “autonomous” system is “composed of webs of interdependent processes whose collective activity is self-generating.”\(^61\) In fact, since autonomous systems are far-from-equilibrium systems, the collective activity of the component processes of such a system is not only collectively self-generating but also distributively—each process contributes to the occurrence of the complex dynamics as a whole as well as to its own occurrence: “Each of the processes that form part of the system requires outputs from other processes in the system to function [i.e., to occur], and in turn contributes to the requirements of other processes.”\(^62\)

While the component activities of a system near-the-equilibrium—e.g., three balls at the bottom of a bowl—also generate the complex they are part of, they do not thereby generate the conditions of their own occurrence, since each can exist independently. In contrast, the metabolism occurring in a living organism is interdependent: on the other components of the self-maintaining dynamics of the organism in the strong sense that it requires not merely an occurrence of a process of the same kind for their existence, but the existence of the very processes they themselves engender.

The notion of an ‘autonomous system’ seems intuitively quite accessible, but its precise ontological characterization is not perfectly straightforward. Strong interdependencies between dynamics can be modeled in GFT by means of circular parthood chains: $[\alpha]_r \subseteq [\beta]_r$, $[\beta]_r \subseteq [\gamma]_r$, $[\gamma]_r \subseteq [\alpha]_r$, or also, with decreasing strength, formulated across partition levels of length N, $[\alpha]_N \subseteq [\beta]_N$, $[\beta]_N \subseteq [\gamma]_N$, $[\gamma]_N \subseteq [\alpha]_N$.\(^63\)

But this would not be sufficient to capture the additional and decisive aspect of autonomous or self-maintaining systems implied in the metaphor of ‘maintenance’: the processes forming such systems or complex dynamics are not only interdependent, they also regulate each other in the sense that the products of their causal interference counteract each other in ways that ensure the continuation of the complex dynamics. The notion of an autonomous system is “a generalization of the notion of an

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\(^{61}\) Christensen and Bickhard (2002, p. 3).

\(^{62}\) Ibid, p. 4.

\(^{63}\) An even stronger version of interdependence would move from circular to totally distributive dependencies, where each process “requires output” from each of the other processes that are part of the autonomous system. However, this formulation of interdependence seems too strong—there are certainly parts “composing” an autonomous system, even parts “generating the conditions for the system’s cohesion,” (Ibid. p. 19) that depend only on some of the other parts of the system. For instance, the melting of wax in a candle flame, the “canonical example” of an autonomous system, depends on the burning of the flame but not on the air convection. Christensen/Bickhard acknowledge that “patterns of interdependence will generally be complex and sometimes asymmetrical” (p. 20), but offer no detailed definition of the interdependence of processes that is characteristic for autonomous systems.
autocatalytic reaction,” but even more precisely, a generalization of the notion of the special class of ‘entangled’ autocatalytic reactions. Consider for instance the dynamical structure of the Belousov–Zhabotinski Reaction:

1. \( \text{A} \rightarrow \text{B} \)
   \( \text{A} + \text{B} \rightarrow 2\text{B} \)
2. \( \text{B} + \text{C} \rightarrow 2\text{C} \)
   \( \text{C} \rightarrow \text{D} \)

Such so-called ‘chemical clocks’ oscillate between two dynamic ‘states’ associated with ‘B’ and ‘C,’ given the continuous addition of A and removal of D, since the first reaction triggers the second, while the second limits the first. In a similar fashion, the dynamic structure of a self-maintaining system contains entanglements of ingredient processes but here the regulatory influence among these is even more comprehensive. Consider for example the partition of a burning candle flame in region r:

1. Parts of \([\alpha]_r\) = combustion: \([\beta]_r\) = consuming oxygen, \([\gamma]_r\) = generating heat; \([\delta]_r\) = consuming fuel; \([\varepsilon]_r\) = producing residues.\(^{65}\)
2. Products of causal interference of \([\gamma]_r\) with \([\kappa]_{r+m}\) = wax and \([\lambda]_{r+n}\) = air: \([\eta]_r\) = melting of wax, \([\xi]_r\) = air convection.
3. Products of causal interference of \([\eta]_r\) and \([\mu]_{r+k}\) = wick: \([\theta]_r\) = liquifying wax, \([\iota]_r\) = coating wick.
4. Product of causal interference of \([\xi]_r\) with \([\lambda]_{r+m}\): \([\upsilon]_r\) = oxygen supply
5. Product of causal interference of \([\theta]_r\) with \([\mu]_{r+k}\): \([\phi]_{r+k}\) = wax percolating up (fuel supply).
6. Product of causal interference of \([\xi]_r\) with \([\varepsilon]_r\): \([\pi]_{r+t}\) = residue removal.

As apparent, the ingredient processes of a self-maintaining dynamics (both at a partition level and across) causally interfere to create interference products that reverse those developments that will lead to the equilibrium state. Thus, at a closer look the distinctive feature of self-maintaining dynamics is not so much the positive feedback structure of an autocatalytic reaction, but the negative feedback on those of its ingredient processes that produce the system’s disintegration. Such a disintegrative process \(\alpha\) (e.g., the development reducing the quantity of fuel) can be understood as negative feedback on a dynamics \(\beta\) (e.g., the quantity of fuel) that is involved in a part of \(\alpha\) (i.e., is a n-part of \(\alpha\)). To counteract the negative feedback, another process needs to produce a suitable replacements of \(\beta\) (e.g., another quantity of fuel) or, alternatively, negative feedback on \(\alpha\). Thus we receive the overall schema (let region r be spatiotemporally included in s):

\[\text{(S5: Dynamic schema of a self-maintaining dynamics } \alpha)\]

For all \([x]_r\), \([y]_r\) with \([x]_r \subseteq [\alpha]_r\), and \([y]_r \subseteq [\alpha]_r\), if negative feedback \([x]_r\), \([y]_r\), then

(i) there are \([z]_r\), \([u]_r\), \([v]_r\) \(\subseteq [\alpha]_r\) and:

\(^{64}\) Christensen and Bickhard (2002).
\(^{65}\) These terms denote to complex dynamics that have more fine-grained physical descriptions.
(ii) \([z]_t = \text{causal interference (}[u]_t, [v]_t, [w]_{t+n})\) and it holds for the interference product \([w]_{t+n}\):

(iii) \([w]_{t+n} = \text{causal interference (}[k]_t, [l]_t, [y]_t)\) or negative feedback \((w]_{t+n}, [x]_t)\).

As the schema displays, the process \(w\) counteracting the disintegrating \(x\) is the interference product of two (or more) component processes of the self-maintaining system (dynamics) but may extend beyond the spatial region of the latter into the system’s environment (e.g., fuel import).

There are four aspects of the schema (S5) that I want to highlight here in particular. First, (S5) is defined without explicit reference to far-from-equilibrium systems. Even though far-from-equilibrium systems are probably the largest and most distinctive type of self-maintaining interaction dynamics, there are some advantages, I believe, in defining the relevant interaction type in terms of dynamic structure alone, especially if the concept of autonomy or self-maintenance is to apply also to “socio-cultural systems such as businesses, cities, geo-political regions, and nations.”66 This should not detract from the fact, however, that the focus on far-from-equilibrium systems provides a clear sense of the functionality of (some of) the component processes of this interaction dynamics: the processes in clause (iii) maintain the dynamics they are themselves part of. Second, given the existential quantification in (i), the schema captures only the relevant interdependence relations between the parts of a self-maintaining dynamics, allowing for embedded types of interactions of a different type (e.g., mechanisms).67 This has also the consequence, however, that only those parts and n-parts of a self-maintaining dynamics can be said to serve a function that counteract disintegrating processes, as well as those that causally produce such counteracting processes; some parts and n-parts of such a dynamics will be dysfunctional (e.g., the production of residue) or neutral. Third, the schema is easily extended to represent the interaction dynamics of so-called “recursive self-maintenance,” the “ability to maintain the property of being self-maintenent in the face of variations in relevant conditions that determine what will be self-maintenent and what not.”68 Systems that are capable of interacting with their environment so as to maintain the conditions under which they can maintain themselves (e.g., by swimming towards a food source) can enable the processes described in clause (iii) along alternative causal pathways based on different interactions with the environment. Fourth, self-maintaining systems and other complex systems are frequently said to display a characteristic resilience or robustness under slightly fluctuating environmental conditions. Often this resilience is due to recursive self-maintenance, but not always—a candle flame is remarkably stable in the wind. A suitable ontological analysis thus should allow for any self-maintaining interaction dynamics to vary in its concrete composition over time. On the premises of traditional ontologies, i.e., ontologies abiding by what I called above the ‘myth of substance,’ this is an impossible task. For on traditional premises any concrete individual is taken to be fully determinate and thus ‘robustness’ can only be interpreted in terms

66 Christensen and Bickhard (2002, p. 4).
67 Cf. note 62.
of the variability of what counts as the instantiation of a universal or type. This in turn implies that the component processes of such a concrete instance maintain at best the dynamics as type, but not themselves.\textsuperscript{69} In contrast, since in GPT concrete individuals are more or less schematic or indeterminate, concrete complex processes can maintain themselves in a literal sense and yet allow for some variation in the processes they involve.\textsuperscript{70}

4.6 Towards a typology of emergent interactions

So far I have offered characterizations of different types of emergent interaction in terms of the dynamic structures of the processes involved. One might object that the usage of the adjective ‘emergent’ in the foregoing is gratuitous since I have not laid down any conditions for when an interference product can be properly said to be ‘emergent.’ The minimal condition mentioned above that the interference product must not occur in the partitions of the interfering dynamics can be combined with any of the currently discussed definitions of emergence. For example, one might in addition demand that the interference product should fulfill a suitably formulated requirement of nonlinearity or non-aggregativity, or should involve ‘downward causation’ (i.e., in the terminology developed here, should regulate some n-parts of the interfering dynamics), or should not be observable with the methods by means of which the properties of the interfering dynamics are observed.\textsuperscript{71} Further formal distinctions may be drawn in terms of number of partition levels involved—whether the interference focus sums parts that lie at the same partition level of the interfering dynamics, or whether it runs cross-level, which means that one of the interfering dynamics is less centrally involved than the other. Other distinctions in types of emergent interactions can make reference to the kinds of dynamics involved in the interference; for example, so-called ‘first order emergent structures’ are products of interfering dynamics associated with shape features (e.g., surface tension in water resulting from the interference of hydrogen bonds in water molecules), while ‘second-order emergent structures’ are products of such shape interactions played out sequentially over time (e.g., the form of a falling snowflake influenced and is altered by changes in atmospheric conditions.) The five-dimensional classificatory matrix of GPT contains rich means to articulate fine-grained distinctions between types of ‘emergent’ interactions.

5 Conclusion

The definitions and schematic characterizations of types of emergent interactions presented here should be considered as exploratory proposals that need further detail and

\textsuperscript{69} In other words, on traditional premises there is only virtual positive feedback along the schema of (S3) above.

\textsuperscript{70} Formally, these variations pertain to levels $N+n$ of a partition that contains the $N$-partition in terms of which dynamics $\alpha$ is defined.

\textsuperscript{71} Cf. for example Wimsatt (1986), Emmeche et al. (2000), Baas (1992).
perhaps also adjustment. But the main purpose of this paper has been to set a pointer to a line of inquiry rather than a ready-made theory, and to provide at least some relevant support for the claims (a) that it is possible to offer precise ontological analyses of interactive processes, and (b) that there are some benefits to be expected from such an enterprise, for the theoretical aims of both interactivism and ontology. There are two more specific corollaries to these claims that the foregoing considerations might have made plausible as well. (a-1) The analysis of interactive dynamics makes extraordinary demands on an ontological theory that the ontological main alternatives currently under discussion (ontological frameworks based on states of affairs, substances or objects, tropes or events) cannot fulfill—only frameworks that relinquish the traditional premises of the ‘myth of substance’ can consistently make sense of concrete dynamics that are literally self-maintaining. Since it is in terms of such self-maintaining dynamics that—as interactivists have argued—normative functionality can be naturalistically defined, this shortcoming of traditional ontology is momentous. (b-1) Echoing to some extent a position that William Wimsatt has argued on different grounds, I have suggested here that emergence is ubiquitous: even mechanistic interactions are a special type of productive interferences of dynamics. The sense of ‘emergence’ at issue here is compatible with reductive causal explanations of emergent dynamics, and thus quite different from what typical ‘emergentists’ would canvass. But it can serve to show that the ontological gestalt switch from a world of inert objects to a world of interaction dynamics will relocate and to some extent deflate the familiar debate about emergence versus reduction—what used to be a debate about the ontological status of complex entities would then pertain merely to the proper classification of interaction dynamics.

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