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Can There be a Process Without Time? Processualism Within Timeless Physics

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Abstract

Process ontology is making deep inroads into the hard sciences. For it offers a workable understanding of dynamic phenomena which sits well with inquiries that problematize the traditional conception of self-standing, definite, independent objects as the basic stuff of the universe. Process-based approaches are claimed by their advocates to yield better ontological descriptions of various domains of physical reality in which dynamical, indefinite activities are prior to definite "things" or "states of things". However, if applied to physics, a main problem comes up: the notion itself of process appears to pivot on a conception of evolution through time that is at variance with relativistic physics. Against this worry, this article advances a conception of process that can be reconciled with general relativity. It claims that, within timeless physical frameworks, a process should not be conceived as activities evolving through time. Rather, processes concern the identity that entities obtain within the broader sets of relations in which they stand. To make this case, the article homes in on one of the physical approaches that most resolutely removes time from the basic features of reality, that is, canonical quantum gravity. As a case in point, it addresses Carlo Rovelli's Evolving Constant approach as a physical paradigm that resolutely rejects time as an absolute parameter and recasts processualism as an inquiry into how physical systems affect one another.

Keywords Evolving constant approach · Process · Relativistic physics · Substance · Timelessness

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1 Introduction

In the last decades, the notion of process has been advocated in a variety of disciplines and research areas.[1] Despite the differences in how this term has been characterized, there is at least one core feature that all versions of process thinking seem to agree upon. The idea that individual, concrete, definite substances are the fundamental entities of natural languages and scientific theories is basically flawed. Although, as I will clarify below, substance metaphysics is still the prevalent metaphysical view, process metaphysics contends that there are more fundamental entities that are individuals without being either countable or definite. These are processes from which, as I will discuss, individual, concrete, definite entities can be abstracted.

The notion of processes being more fundamental than particular, definite entities (such as objects or particles or spatiotemporally delimited events) seems to be based, and for many process theories is based, on the relation between objects without temporal parts and processes with temporal parts. In brief, three-dimensional definite entities are abstracted from four-dimensional processes that are indefinite in the sense that they cannot be identified based on specific spatiotemporal coordinates. Processes are concrete, non-particular, and non-countable activities that do not occur in a unique spacetime location. Within such a processual framework, concreteness and non-particularity are generally couched in terms of evolution (for example, particle collision, radioactive decay, phase transitions), while evolution is intimately coupled with becoming. Insofar as processes are more fundamental, and definite individual objects are abstracted from them, process metaphysics insists that the identity of individuals can count on none of the features that are singled out within substance metaphysics. Their identity derives its origin from activities occurring in multiply disconnected spatiotemporal regions. To give an example, within biology and the philosophy of biology, the identity of molecules, cells, organs, organisms, and so on cannot be ascertained based on their intrinsic properties. The identity of these entities is contingent on *what they do* in terms of a dynamical evolution through time. This means that rather than intrinsic properties, what is relevant to the identity of these entities is their activity within a process that has temporal parts. In this frame, Nicholson and Dupré [4, p. 12] comment that a starting point for all process thinking is that "processes are extended in time: they have temporal parts". This implies that the identity of definite, individual entities is tied to the history of concrete, non-particular activities, viz., processes.

It should come as no surprise that, within theoretical physics, this notion of processual identity turns out to be highly problematic. For one of the most debated issues, at least from relativistic physics onwards, is precisely the nature of time. If, as I will illustrate, time cannot be conceived as a linear parameter that can be uniquely defined, let alone a receptacle in which activities take place, what is left of the notion of process sketched above? While considering the anti-substantialist and anti-essentialist stance of processualism, Guay and Pradeu [8] explain that in order

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[1] A few remarkable examples are, in theoretical physics [1]; in metaphysics and the history of philosophy [2, 3]; in biology [4]; in theoretical chemistry [5, 6]; in social sciences [7].

to gain knowledge of an object, what counts is not so much the question "what is X fundamentally?", as it is the question "how should I *follow* X through time?" [8, p. 318]. However, this begs the question of how one can follow X through (what) time. Certainly, what relativistic physics rules out is the idea that a common, universal timeline can be used for this purpose. Indeed, based on the relativity of simultaneity, contemporary physics (with few interesting exceptions which I will mention below) rejects the existence of time as an absolute parameter. So, if this holds true, *different* events that occur locally along the worldline of *different* systems are taken to be part of *the same* process. This is why a thorny issue in processual thinking is to account for "how different events can be related and seen as characterizing the same individual" [8, p. 320].

Among contemporary physical theories that espouse the idea that physics is primarily concerned with processes rather than events or states of things, the difficulty of identifying what events belong to what process brings about a fundamental conflict. There are physical theories that claim that the idea of process entails the rejection of the relativity of simultaneity exactly because events should be amenable to localization and univocal identification. Hence, these theories submit that processual physics presupposes a notion of *time as fundamental* in that the universe is a process of *unique events* that occur and then cease to be.[2] Therefore, events can be regarded as belonging to the same process if and only if there is an absolute temporal parameter, so much so that processualism in physics entails the rejection of relativity. Other theories, on the contrary, try to recover the notion of process from a relativistic framework and claim that a process is not related to a unique ordering of events. This article will make the claim that this latter strategy is viable, although the notion of process is to be untied from that of time. Accordingly, the main focus of this article will be the idea of process within timeless physical paradigms. I will tackle the question of how a process can be thought of without the notion of linear temporality and why it is relevant to physical theories.

Section 1 will offer a concise overview of the main tenets of process thinking in contemporary metaphysics to identify the advantages that it offers when it comes to theorising the fundamental entities of physical theories. Section 2 will make the

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[2] In this article I cannot delve into the strand of process physics where time is considered to be fundamental and irreversible. However, an example of an influential and intriguing attempt to conceptualize reality as a process of unique events is Marina Cortês and Lee Smolin's. They set out to demonstrate that the notion itself of process invites to reconsider the relativity of simultaneity, as well as its metaphysical counterpart, known as the "block universe". Cortês and Smolin [9] insist that the universe is to be portrayed as a process of unique events in which time is conceived as both fundamental and irreversible (see also [10]). The process that physical theories are concerned with is "continually acting in the present bringing into existence the next moment" [9, p. 1]. Such an understanding of the universe implies a unique temporal sequence and a unique identity for the entities within this sequence. On this account, a process is an absolutely defined activity generating a thick present, such that two events can be causally related to each other in a present that is continually growing by addition of new events. As events in the thick present lose their ability to influence future events, they move into the always growing past (see also [11, 12]). Cortês and Smolin's proposal is particularly interesting because it appears to back up the conclusion that the history of an entity is to be uniquely defined from an absolute point of view. Such a uniqueness is secured by the relational (causal) properties entities stand in. Therefore, Cortês and Smolin submit that no process is conceivable where absolute time gets lost.

case that a genuine notion of process can be derived from a specific interpretation of special relativity (SR) and general relativity (GR)—one that does not concern so much the evolution over time, as the identity of spacetime points. This is John Stachel's view, as he claims that a processual interpretation of GR leads to an idea of identity that is context-dependent. He maintains that spacetime points are not self-standing individuals but inherit their identity from the physical relations imposed on them. This is the same basic conclusion of process metaphysics, though no idea of a unique history of events is implied. Drawing from this understanding of relativistic physics, Section 3 will focus on the way canonical quantum gravity can be framed in processual terms. Canonical quantum gravity is an attempt to quantize GR that is especially important for present purposes because it is one of the physical approaches that most resolutely removes time from the basic features of reality. If there is a way to reconcile process metaphysics and the (claimed) timelessness of canonical quantum gravity, then one can definitely conclude that the idea of process is not necessarily coupled with the idea of evolution through time. To this end, I will concentrate on a particularly instructive version of canonical quantum gravity—one that comes from a specific interpretation of the principle of general covariance and hence espouses timelessness wholeheartedly—that is, Carlo Rovelli's Evolving Constant Approach. Rovelli's attempt at unification holds onto the relativity of simultaneity and yet claims that physics *is* the study of processes.

This article tackles the question of if and how this latter claim can be vindicated. The main contention I will make is that timeless processual paradigms come to an interesting conclusion that slightly amends the notion of process that I presented at the outset. Since a process does not comprise uniquely identifiable events, the identity of the entities that are part of it cannot be identified by following it through time. Rather, the identity of entities such as events or particles gets established with respect to the interaction of physical systems, while systems themselves are to be regarded as abstractions from broader sets of interactions.

2 Process Metaphysics

As I hinted above, the idea of process in Western metaphysics conjures the idea of dynamics. Process metaphysics takes as its object of study a reality that is thought of as continuously changing. In this frame, process metaphysics pits this common-sensical image of a changing reality—something that human beings experience on a daily basis—against what process theorists regard as an obsession of Western metaphysics, that is to say, stable, unchanging substances. These are self-identical, self-standing entities that preserve their identity despite the changes around them as well as the changes in their transient properties. Therefore, to have a full grasp of the notion of process, it is important to pinpoint the critical target of process philosophy. Johanna Seibt [12–15] identifies a few tenets of substance metaphysics that she traces back to the Aristotelian approach, but she argues in-filtrated the whole history of Western metaphysics to the extent that it is not only the dominant para-digm but is regarded as the only possible one.

Substance metaphysics only makes room for two types of entities: concrete and individual ones (such as objects or particles) vs. abstract and universal ones (such as attributes and properties). In this framework, the individuality of an entity depends on its countability and should be identified with reference to a component of the structural description of this entity. The components that identify entities are to be characterized in terms of mutually exclusive features. Individuals cannot be but particulars and only concrete individuals are fully determinate. On the contrary, "concrete non-countable entities like masses and activities indeed appear as ontological monstrosities—they are neither individuals nor universals, or they are some of both" [13, p. 172]. In short, the features identifying substances are independence, subjecthood, persistence, and determinateness, while primitive thisness only refers to individuals of this sort. Against this view, Seibt goes on by qualifying processes as concrete, non-countable, and non-particular activities. They can be individuated based on their descriptive thisness, although they occur in a "multiply disconnected spatiotemporal region with fuzzy boundaries" [14, p. 85]. Therefore, processes defy the categorial features spelled out by substance metaphysics, and particularly the idea that individuals are already and always determinate.

In sum, the main idea is that processes are concrete, though spatiotemporally indeterminate and non-particular, in that they are multiply disconnected. In this sense, the idea of a continuously changing reality, replete with non-particulars, has to do with the absence of clear boundaries, fixed whence and whither. While advocating a notion of process that is not identical to Seibt's, Peter Simons insists that processes are more fundamental than substances as "truth makers for propositions stating the existence of a continuant *at a time*" [16, p. 53]. Unlike occurrents, which "have phases and temporal slices corresponding to the interval and moments through which they perdure" [17, p. 60], a continuant is an entity existing in time which has no temporal parts, that is to say, parts that exist only because they exist at a certain time. Simons claims that at the fundamental level occurrents are prior to continuants. More precisely, continuants are "to be understood as invariant *precipitates* of a species of causal relatedness known […] as genidentity" [16, p. 55], where genidentity is qualified as an equivalence relation between the phases of the continuants and occurrents are processes. Put otherwise, the entities of substance metaphysics are *precipitates* of processes which can be identified based on genidentity among certain process phases. In the light of this, a process view entails continuants being the outcome of an abstraction, which Simons describes as "a species of cognitive operation" that "underlies a significant portion of sophisticated linguistic and scientific practice" [16, p. 56]. In other words, continuants do not themselves have temporal parts, but are obtained through abstraction from occurrents that do. Simons's [17, p. 421] example will be of help:

> I walk across a room. The episode of my walking has phases, it also has natural spatiotemporal parts, this swing of the left leg, that push with the right sole. It has a beginning, a continuation, and an end. I do not have such a beginning, middle, and end: I (and my relevant parts) exist throughout. But simply because there are events and processes involving me going on at these times it is evident that I do exist then. You can't walk if you don't exist. So the sugges-

> tion is that not the continuant but occurrents in its life make it true that it exists then.

Apparently, then, traditional entities known as substances are to be identified based on the processes they are part of, while temporality is crucial for there being occurrents. As I will argue in the rest of this article, there are process theories that have to face the problem of timelessness, which makes temporality problematic, at least in the way it is commonly understood. For the moment, though, let me emphasize a point which I would like to derive from the discussion above and that will be key to my argument below. First, the idea of continuants being abstractions boils down to the rejection of the notion of self-identical, individual, determinate entities as fundamental. These are precipitates, whose existence is conditional on processes. Second, within a process, through abstraction, one can identify multiple continuants. This means that continuants are not endowed with primitive individuality. Rather, they have what could be regarded as possessing a "weak individuality" [18]. Put otherwise, there are multiplicities of nested individuals that can be individuated through abstraction for specific purposes. Again, the idea of a continuously changing reality that is typical of process metaphysics conveys the more concrete notion that within occurrents different individuals can be abstracted, to such an extent that, always based on one's type of inquiry, one can identify a *hierarchy of individuals*. This is quite evident in the field of biology, where "to be individual is to be somewhere in the space of individuality" [18, p. 46]. In other words, what counts as an *individual depends on one's theoretical inquiry* which determines the criterion for picking out a set of entities as *the relevant individuals*. It is based on this basic indeterminateness that Huneman [18, p. 54] elaborates on the notion of *weak individuality*:

> Assuming that individuals are made up of some entities, so that the individuality issue is about which assemblages of entities count as individuals and which ones don't, then among a set of entities whose interactions are known and modelled with respect to a range of parameters (defined in one of our best theories of these interactions), individuals are the subsets of entities that interact most between themselves rather than with the rest.

As I will argue, this understanding of weak individuality sits well with a particular interpretation of relativistic physics. But what counts in this context is the notion of process to which this conception is conducive. In the rest of this article, I will contend that processualism first and foremost concerns the notion of individuality, or better, how entities acquire individuality. Against traditional substance metaphysics, substances are not endowed with strong individuality, as individual entities are amenable to various activities of abstraction. In this sense, individuality is "rather a scheme for extracting individuals on the basis of the theories that elaborate our best models of interaction in a given ontological domain" [18, pp. 56–57]. I will argue that this opens the door to a conception of process that is not pivoted on the notion of time. Processes are to be conceived as nested sets of relations among entities that are individuated through an activity of abstraction which is theory-dependent. As I will illustrate, this is particularly relevant to understanding the basic task of physics. In the following sections, I will drop the terminology of occurrents vs. continuants in that they are not particularly widespread in the field of physics and will rather employ the terminology of entities and relations. Based on a particular interpretation of relativistic physics, my objective in the following sections will be to defend a notion of process as that which happens among systems when they interact.

3 A Processual View of General Relativity

As we have seen, to understand whether or not timeless physics can make room for an idea of process, one has to explore the type of process that emerges from the theoretical paradigm which has revolutionized our conception of space and time. To this end, I will build on physicist and philosopher of physics John Stachel's understanding of GR, as he openly makes the claim that it is inherently processual. So, what notion of process can be squared with GR? Stachel's analysis gets underway with the discussion of the so-called *hole argument*, which dates back to Einstein himself. GR is a generally covariant theory which, to put it simply, means that its laws are invariant under coordinate transformations. As a consequence, if one starts with one model of GR and applies a *diffeomorphism*, then a certain physical state can be described in two different manners, respectively corresponding to one or the other model. The hole argument comes down to the fact that, while the two models describe observationally equivalent state of affairs, the applied diffeomorphism produces a different correspondence between the physical state and spacetime points.

In the first decades of the 20th century, this issue sparked various interpretative conflicts among scholars (see e.g. [19–21]). After a period in which the issue was put in abeyance, the argument encountered a modern revival from the 1980s on, with Earman and Norton [22] and Stachel himself [23]. In a recent survey of the hole argument, Stachel [24, p. 6] observes that the issue is of particular theoretical import as, on his reading, it "shows that, for any theory defined by a set of generally-covariant field equations, the only way to make physical sense of the theory is to assume that the entire equivalence class of diffeomorphically-related solutions to the field equations represent a single physical solution". Because of this, he concludes that physical theories should be written in a fully background independent fashion so as to meet the principle of general covariance.[3] While I will return to this topic,

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[3] According to Earman [25], there are two notions of general covariance, namely *formal* and *substantive*. A spacetime theory fulfils formal general covariance if its physical laws are valid in every coordinate system, provided that they are valid in one of them. Drawing from Kretschmann's [26] analysis on general covariance, the formal version of general covariance bears no real physical content. Rather, it is a certain type of formulation which can be applied to any physical spacetime theory (such as Newtonian spacetime theory or Special Relativity): "This is a condition of the well-formedness of a theory, not on its content" [25, p. 4]. On the other hand, a spacetime theory satisfies the substantive requirement of general covariance if its laws are diffeomorphism invariant. A theory is diffeomorphism invariant if its physical laws are invariant under arbitrary coordinate transformations. In this regard, Kuchar [27] states that the content of the general covariance of GR does not consist in the fact that it can be expressed in a generally covariant formulation (like every other physical spacetime theory). Rather, the point is that GR can only be written in a generally covariant fashion. For the very content of the theory resides precisely in that it does not depend on the existence of a preferred coordinate system or geometrical structure. I should like to note in passing that, interestingly enough, canonical quantum gravity operates via a $3+1$ split of the four-dimensional manifold of GR which, according to some physicists, is not the right way to proceed. It

what is worth emphasizing at this stage is that Stachel invokes the hole argument to defend a processual account of physics.

Stachel commences by singling out algebraic and geometric structures. If one takes a set of elements $S = \{1,2 \ldots N\}$ endowed with a set of relations between its elements, call it R, a distinction can be defined between a geometry and an algebra. In a geometry, the elements of the set exhibit the same *quiddity* (which Stachel calls the "natural kind" [29, p. 56]) but no *haecceity* (which Stachel defines as the "unique individuality" or "primitive thisness" [29, p. 56]). If the internal relations between the elements of the set are omitted, then the set $S = \{1,2 \ldots N\}$ is invariant under the permutation group. Thus, it is only by taking into account the set of internal relations among the elements that one can be individuated vis-à-vis others. Vice versa, the elements of an algebra exhibit both quiddity and haecceity, as they are put in a one-to-one correspondence with a numbered coordinate system. As Stachel [24, p. 20] illustrates, it is normally convenient, or even necessary, to perform a coordinatization procedure whereby each geometrical element gets referred to an algebraic coordinate. As a consequence, the geometrical homogeneity gets lost. In order to restore it, one has to consider all the admissible coordinate transformations of the geometry in a given algebra. Thanks to this methodology, each element of the geometry gets assigned to all the possible algebraic coordinates in at least one admissible coordinate system.

A transformation between two admissible coordinate systems can be achieved in two different manners, each corresponding to a different transformation. In an *active point transformation*, one keeps the coordinate system unchanged and permute the points of the geometry. In a *passive coordinate transformation*, one vice versa keeps the geometric points fixed, and performs an admissible coordinate transformation of the elements of the algebra. Each set $=\{1, 2\ldots\}$ is then characterized by equivalence relations. An equivalence relation is a reflexive, symmetric and transitive two-place relation. An equivalence relation splits the set $= \{1, 2\ldots\}$ into *equivalence classes*, also termed *orbits*. Every element of the set corresponds to one and only one such equivalence class. A certain theory is permutable if, given a certain model for the theory, the overall equivalence class of that model is still a model for the theory. A certain theory is generally permutable if the entire equivalence class is taken as a single model of the theory.

Based on this analysis, Stachel interprets the principle of general covariance as a principle of geometrical homogeneity. In other words, he argues that spacetime points do have quiddity, but lack intrinsic haecceity. And this metaphysical position—which he dubs *dynamic structural realism*[4]—leans towards a form of realism

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Footnote 3 (continued)

is in order to make up for this that, for example, Rovelli and Vidotto [28] advanced a covariant version of Loop Quantum Gravity.

[4] According to Stachel, this metaphysical position resonates with Dorato's [30] structural spacetime realism or the sophisticated substantivalism advanced by Pooley [31]. Dynamic structural realism entails that the points of the spacetime manifold do have physical character even before a certain metric field is chosen—and this is why Pooley [32] places it within the substantivalist family. However, spacetime points lack individuality, or haecceity. On this respect, Stachel's processualism calls for a distinct, and yet highly connected, debate, that is, that of ontic structural realism (OSR). Despite the differences in how it

which underlines the *priority of processes over states* [24, p. 38]. For a state is "just a particular spatial cross-section of a process and of secondary importance: all such cross-sections are equal, and each sequence of states represents a different 'perspective' on the same process" [24, pp. 65–66]. In other words, a state is subject to the same condition that applies to spacetime points, as a state gets its identity from something which is not intrinsic to the state itself. The fact of there being a state depends on one's picking up a specific frame of reference that defines a physical state. As a consequence, any breakup is to some extent arbitrary—viz., a conceptual abstraction for specific purposes.

To sum up, Stachel's treatment of the hole argument arrives at the conclusion that physical states as well as spacetime points are not self-standing individuals but inherit haecceity from the physical relations in which they stand. It is only when something is taken to be part of a set of relations that one can speak of entities with haecceity, as long as these entities are not abstractively isolated from the rest but are taken to be the bearers of relations. On this account, a process is the moment at which an entity is taken to be an individual within a set of relations. Though we still have to see what happens when processualism is married to timelessness, GR paves the way for a conceptualization of process that evades the issue of the unique identifiability of events, in that it breaks with the metaphysics of things as isolated self-identical entities to the advantage of a relational (Stachel [40], would say *contextual*) notion of identity.

4 Rovelli's Evolving Constant Approach

Stachel's processual account of physics is centred on GR, which is a classical theory. However, one may wonder whether this approach can be extended to other theoretical contexts in which GR is coupled with quantum mechanics. This type of inquiry is particularly important because nowadays unification is one of the leading research paths within theoretical physics. For Quantum Field Theory (QFT) and General Relativity (GR), which are the most fundamental theories we currently have, turn

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Footnote 4 (continued)

has been characterized, OSR is a metaphysical conception whose main tenet is that "what there is in the world at the fundamental level […] are physical structures, in the sense of networks of concrete physical relations among concrete physical objects (relata)" [33, p. 1157]. As Lam [34] explains, OSR comes in diverse ways. The radical, or eliminativist version, first developed by French and Ladyman [35], argues that all that exists is nothing other than structures. Objects are not admitted in this ontology, whereas there are relations "all the way down". In its moderate version, such as that developed by Esfeld and Lam [36], OSR does admit objects in the ontology, but these objects are regarded as deriving from the more fundamental physical structures in which these objects stand. In a similar vein, Stachel's theoretical position leans towards a form of structuralism, different from the eliminativist OSR *à la* French [37, 38] which "stresses the priority of processes over states" [24, p. 38]. While I cannot further expand on this topic here, the relation between Stachel's processualism and OSR is something that would deserve an in-depth analysis, as well as that between processualism and fundamentality (for a parallel discussion on the relation between ontic structuralism and fundamentality, see [39]).

out to be effective field theories (EFTs).[5] This means that they present restricted domains of prediction, out of which divergence arises (see e.g., [43, 44]). So, in the present context, it is worth investigating whether processualism is also applicable within so-called Quantum Gravity (QG). While there is general agreement about its broad definition—namely, a theory about the microscopic structure of spacetime—the main disagreement lies in the methodology from which such a theory can be advanced [45]. Following Huggett et al.'s [46] classification, three main approaches can be singled out. The first holds that QG results from a quantization of GR, a highly prosperous theory for the macroscopic, classical structure of spacetime. The second draws from quantum theories of matter and aims at extending them to make sense of the gravitational field and their mutual interactions. Finally, the third one entails a more revisionary approach that replaces existing theories for novel principles that are meant to articulate a novel theory of quantum gravity from scratch.

While it is not for the present work to offer a reconstruction of the various and at times incompatible approaches to QG, my purpose here is to expand on a specific theoretical proposal that is particularly relevant to the present discussion, in that it stems from an interpretation of the principle of general covariance that seriously undermines the notion of temporal evolution, and *a fortiori* temporal linearity. This is Rovelli's Evolving Constant approach. My objective is to show that, though Rovelli's approach is one of those that most resolutely espouse timelessness, his theoretical framework is nevertheless hospitable to a notion of process. For Rovelli's interpretation of physics broadly conceived, whether in the field of classical physics or quantum mechanics, is such that "the best description of reality is the way things can affect one another" [47, p. 280]. While this might be interpreted as relationism all the way down, Rovelli goes to great lengths to subsume this understanding of relation under the scope of process thinking. He makes the claim that interactions among things should rather be understood as processes, which he takes to be as the fundamental entities of physical reality. Processes is what we should draw attention on so as not to espouse an objectifying view of entities: "It is better to describe reality in terms of interactions rather than objects, thereby concentrating on a process and not on entities" [47, p. 280]. Thus, while Rovelli never concerned himself with spelling out what a process is in metaphysical terms, it is worth trying to investigate how his relational conception of relativity could be better described in processual terms.[6]

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[5] For a proper characterization of the notion of EFT see e.g., [41]. As she explains, an effective theory (ET) is a theory which has a certain domain of validity. Drawing from Georgi's [42] analysis, Castellani conceives an ET as "an appropriate description of the important (relevant) physics in a given region of the parameter space of the physical world" [41, p. 260]. As physics displays highly differentiated behaviour at different energy scales, ETs are intrinsically approximate. In this article, Castellani explores the relevance of EFTs in the context of particle physics.

[6] I would like to add in passing that a process reading of Rovelli's relationalism also helps tease out a few key differences with other kinds of relationalism, especially those that dispose of the notion of becoming—which is something Rovelli holds onto in the form of local becoming. As a paradigmatic case, one should only think of Julian Barbour's [48, 49]) relationalism, as it was deployed in his shape dynamics, which amounts to an utterly adynamical configurational relationalism—a configuration being a specification of all inter-particle distances at some instant. In this theoretical framework, relationalism is but of locations and scale (see Gomes [50]), and pivots on the notion of instantaneous relative

Rovelli's [52–56] Evolving Constant approach, which belongs to the first group (the so-called canonical approach to QG) of Huggett et al.'s [46] classification, starts from a gauge-invariant interpretation of the principle of general covariance that pivots on a conceptualization of properties as not intrinsic, but *relational*. Rovelli's idea is that of implementing a one-parameter family of observables that can constitute the types of changing properties displayed at the classical macro level. The point is thus to substitute intrinsic properties (such as "the mass of this object is x") with relational properties (such as "the mass of this object is x with respect to y"). This claim is particularly relevant for my purposes in this article in that it allows conceiving individuals (objects, aggregates, bodies) within a non-essentialist frame, in the sense that their identity can only be determined with respect to the network of relations in which they are taken under consideration. Even more importantly, as the networks in which an entity can be included are multiple, no entity is uniquely definable. A decisive implication of my argument is that, if one wants to hold a processual view of physics that is compatible with relativistic physics, one should accept the idea that the identity of entities is itself multiple. As far as the Evolving Constant approach is concerned, it does fit this picture: while individuals do not display any intrinsic property, gauge-invariant parameters encode the variation of the entities' properties.

To make this point, it is imperative to introduce Rovelli's [55] distinction between *partial* and *complete observables*.[7] In the gauge-invariant interpretation of a gauge theory one distinguishes between gauge-invariant quantities (observables) and gauge-dependent quantities (non-observables).[8] Naturally, there are several issues concerning the notion and status of observables. To this end, Rovelli argues that, as

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Footnote 6 (continued)
configurations. On this account, all that exists in the universe, at any particular instant, are patterns of configurations relative to each other. These configurations replace instants of time of classical Newtonian mechanics. Within the distinct configurations there is no evolution or change. The classical Newtonian trajectories correspond to a subset of the total possible relative configurations satisfying a timeless implementation of the principle of least action. Quite the reverse, Rovelli is not concerned with instantaneous descriptions of the universe, but with the coming-into-being of events, in that, for him, physics, whether classical or not, is to make sense of "real becoming in the universe" [51, p. 1331]. This is why relationalism concerns interactions in the first place, and of a type that I suggest understanding in processual terms.

[7] Unfortunately, in this context I cannot unpack the interesting implications that the notion of observables has with the debate on monism vs. pluralism. I would also like to mention Dorato's [57] interpretation of Rovelli's relationalism as Dorato makes the case that it is not compatible with monism, and in particular the priority monism advocated by Schaffer [58], especially when it comes to temporal becoming. Any kind of monism entailing a view of the world as a vast entangled hole is at odds with Rovelli's notion that "the state of any quantum system is a codification of outcomes of previous interactions. Due to the impossibility of interacting with something of which we are a proper part, a large part of the universe can be in an entangled state only relatively to a small, proper part of it" [57, p. 258]. This pluralistic view of Rovelli's relationalism makes sense of how events are the products of interaction between physical systems that can have properties relative to the systems with which they interact, ones that do not exist vis-à-vis the systems with which they do not have an interaction.

[8] This distinction is valuable insofar as it relates with several issues concerning observability. First, whether or not time can be conceived as an observable in quantum mechanics. Second, what quantities should be accorded observability in GR. Third, whether or not the notion of observability should be conferred only to those quantities that commute with the scalar constraint (the so-called Wheeler-DeWitt operator) in quantum gravity. The notion of observability is directly connected with that of measurability. A measure gives us information about the state of a physical system.

a preliminary step, one needs to characterize two distinct notions of observability. A *partial observable* is a physical quantity for which a measurement procedure can be established. A *complete observable* is a physical quantity whose value (or probability distribution in the case of quantum theory) can be predicted by the relevant theory. On this view, partial observables can be measured but not predicted, while complete observables are correlations between partial observables, and they can be both measured and predicted.

The main point to be addressed here is how to derive complete observables (such as the total energy of a system) from partial observables (such as spacetime coordinates in GR). To tackle this question, Rovelli offers a further classification in terms of *dependent* and *independent variables*. This distinction can be conceived in the following way. Consider two partial observables q and t (position and time); then, if it is possible to write q in terms of t, namely as q(t), but this function is not reversible, namely t(q) is not admissible, then q is a dependent partial observable and t is an independent partial observable. While in pre-relativistic theories the distinction between dependent and independent partial observables holds, Rovelli [55, pp. 3–4] argues that in the context of GR the situation is completely different[9]:

> The key difference between general relativistic physics and pre-GR physics is the fact that in general relativist physics the distinction between dependent and independent partial observables is lost. A pre-GR theory is formulated in terms of variables (such as q) evolving as functions of certain distinguished variables (such as t). General relativistic systems are formulated in terms of variables [...] that evolve with respect to each other. General relativity expresses relations between these, but in general we cannot solve for one as a function of the other. Partial observables are genuinely on the same footing.

On this view, the theory describes the evolution of partial (gauge variant) observables *with respect to each other.*[10] All these partial observables are equivalent. None of them can be taken as an independent, privileged parameter vis-à-vis others. In the context of QG, operators corresponding to physical observables must commute with the Wheeler-DeWitt constraint operator, which encodes the temporal evolution. This means that physical observables must be

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[9] On the one hand, in a non-relativistic context, where the spacetime structure is taken as fixed, no distinction between these two definitions of observable can be grasped. On the other hand, in a generally relativistic context, where the spacetime structure is dynamical, the difference between these two notions of observability arises.

[10] In the context of GR, Rovelli [55] offers an instructive example to grasp the idea that no partial observable is independent (and thus, somehow, privileged) with respect to others. Consider a very accurate clock which is mounted on a satellite of the GPS system. This clock transmits its local time, whose signal is collected by the launching base and compared with the time of an equally accurate clock mounted on the base. As a result of the different positions of the clocks, the timing shows a discrepancy due to generally relativistic effects. Rovelli calls t_s and t_b respectively the signal received from the satellite and the local clock reading. General relativity can then be employed to predict the relation between these two partial observables $f\left(t_s;t_b\right) = 0$. In this case, two partial observables can predict another one, f, which is then a complete observable, according to the classification above mentioned. A question naturally arises: which one of them should be referred as the independent variable? One might say that t_b should be favored, as it refers to our commonly reference time. However, t_s corresponds to an accepted standard of time. Clearly, none of them can be chosen as the independent one.

time-independent or time-invariant. The point is then how to describe evolution by means of invariant quantities and whether or not a viable notion of process still obtains within this theoretical framework.

The gist of this approach is that the coordinate time and the physical evolution of systems are independent concepts. In order to get the evolution of systems, one needs to start with the extended configuration space, consider a function of the variables under scrutiny, and thus determine the dynamics. The dynamics is referred to as the mutual variation of these partial observables. While none of them displays a well-defined evolution (*qua* partial, and thus non-predictable observable), the correlation between these partial observables is well defined and thus independent of the temporal parametrization. One of these partial observables is arbitrarily taken as a reference clock. This procedure is of practical interest but indicates nothing about the ontological status of this variable. Spacetime coordinates are indeed partial observables, meaning that they cannot be predicted. They can just be employed to localize complete observables.

Contrary to physical process theory, there is no viable methodology whereby a sequence of events can be defined in a unique way. Rather, given that Rovelli [55, p. 5] portrays physics as the study of the relation between partial observables, the idea itself of entities having self-identical, intrinsic identity is to be dismissed. Physical relations are contingent upon a specific, conventional set of parameters. It is only by fixing a subset of partial observables that the other ones can be written in terms of this subset and thus acquire identifiability.

It is in this sense that Rovelli's relational account of physics can be couched in processual terms. While he rejects the idea that the universe can be portrayed as a process of unique events, a processual physical theory describes the way in which "arbitrary partitions of nature affect one another" [28, p. 52] within the causal structure of the 4-dimensional spacetime geometry of GR—while these partitions have no stable identity of their own. As a result, the identity of a physical system can only be accounted for with respect to other physical systems, with which the former interacts. Even more importantly, from this processual stance, since all these physical systems are to some extent arbitrary—as there is no univocal way to fix their boundaries, like an absolute temporal ordering—so is their identity. In other words, the price that is to be paid to endorse a kind of processualism paired with timelessness, at least within the Evolving Constant approach, is to understand a process as something neither unique nor absolutely definable.

While the process is not one, as is the view of those physicists who think that the notion of process is contingent on an absolute temporal parameter, there are as many processes as the systems that interact with each other, whereas the systems that are included into these processes vary their degrees of freedom based on the way in which they are described with respect to other systems. It is precisely in this sense that Rovelli rejects the idea that a gauge is to be understood as a mere mathematical redundancy. Indeed, whenever systems are not considered in isolation, but with respect to the surrounding environment, then gauge variant quantities, viz. partial observables, are to be taken into account. To put it otherwise, whenever systems are considered with respect to each other, they can be coupled through gauge variant quantities whereby relational properties among them can be defined. In Rovelli's [59, p. 103] words:

> Gauge invariance is not just mathematical redundancy; it is an indication of the relational character of fundamental observables in physics. These do not refer to properties of a single entity. They refer to relational properties between entities: relative velocity, relative localization, relative orientation in internal space, and so on.

Fully to appreciate this point, let me end this section by addressing a particularly instructive example discussed by Rovelli [28]. Take a system composed of a set of N variables $x_n(t)$ (with $n = 1, \ldots, N$) and consider the Lagrangian encoding the dynamics of the system, namely:

$$L_x = \sum_{n=1}^{N-1} \left(\dot{x}_{n+1} - \dot{x}_n\right)^2 \tag{1}$$

(As a potential term would not affect the present discussion, we are ignoring it for the sake of the argument). Clearly, the equations of motion are invariant under the gauge transformation:

$$x_n \to x'_n = x_n + \beta \tag{2}$$

For an arbitrary function $\beta(t)$. This corresponds to what Rovelli dubs a “minimal prototype of a gauge system” [28, p. 93]. Starting from this system, one can define a complete set of gauge-invariant quantities given by:

$$a_n = x_{n+1} - x_n \,\text{with}\, n = 1, \ldots, N-1 \tag{3}$$

Contrary to the evolution of $x_n(t)$, which is under-determined by the equations of motion, that of the a_n follows deterministically. If one only accords physical meaning to the gauge-invariant quantities of the system, then Eq. (1) is equivalent to:

$$\tilde{L}_x = \frac{1}{2} \sum_{n=1}^{N-1} \left(\dot{a}_n\right)^2 \tag{4}$$

Rovelli’s intent is to question this point. To this end, he considers a second system composed by a set of variables $y_n(t)$ (with $n = 1, \ldots, M$), whose dynamics is governed by the corresponding Lagrangian:

$$L_y = \sum_{n=1}^{M-1} \left(\dot{y}_{n+1} - \dot{y}_n\right)^2 \tag{5}$$

Analogously to the previous case, the equations of motion are invariant under the gauge transformation:

$$y_n \to y'_n = y_n + \beta' \tag{6}$$

For an arbitrary function $\beta'(t)$. Again, one can define an equivalent system, $\tilde{L}_y$, with respect to the gauge-invariant quantities $b_n = y_{n+1} - y_n$, thus obtaining:

$$\tilde{L}_x = \frac{1}{2} \sum_{n=1}^{M-1} \left(\dot{b}_n\right)^2 \tag{7}$$

Now, suppose we want to consider the coupled system defined by the variables x_n and y_n, whose dynamics is governed by the total Lagrangian:

$$L_{tot} = L_x + L_y + L_{int} \text{ with } L_{int} \text{ corresponding to} \tag{8}$$

$$L_{int} = \frac{1}{2}\left(\dot{y}_1 - \dot{x}_N\right)^2 \tag{9}$$

In this case, the coupled system is invariant under the gauge transformations (2) and (6) if $\beta(t) = \beta'(t)$. However, notice that the coupled system displays more gauge-invariant quantities than those of the individual systems taken alone, insofar as they are given by the sum of the gauge-invariant quantities of the two systems plus a new one, namely $c = y_1 - x_N$, which depends on y_1 and x_N, corresponding to two gauge-variables of both systems. Now, if one considers only gauge-invariant quantities as physically meaningful, and thus treats gauge-variant ones as mere mathematical redundancy, one should be able to explain how to recover the coupling of the two systems, L_x and L_y, by simply considering $\tilde{L}_x$ and $\tilde{L}_y$, without needing to add any additional variable. But here we face a clear problem, for the degrees of freedom of $\tilde{L}_x$ and $\tilde{L}_y$ is $(N-1)+(M-1) = N+M-2$, whereas the degrees of freedom of L_{tot} is given by $(N-1)+(M-1)+1 = N+M-1$, namely, one more. This means that we can recover L_{tot} from $\tilde{L}_x$ and $\tilde{L}_y$ only by including an additional variable. This begs the question: Why should we do this? Indeed, we already have this additional variable for free by simply considering the union of both L_x and L_y gauge-variables. This is why Rovelli concludes that gauge variables do have a direct physical role, which becomes manifest whenever one pairs systems to each other. In his words [28, p. 103]:

> The thesis of this paper is not that restricting to gauge-invariant observables is wrong. We can always enlarge a system to include any other coupled system and apparatus. [...]. The thesis of this paper is that restringing to gauge invariant observables makes us blind to a fine structure of the world.

In sum, the idea is that whenever one considers systems with respect to each other, gauge-variant quantities do contribute to the total degrees of freedom of the coupled system, and thus to its total set of properties. This explains why Rovelli's relationalism is to be measured against process ontology. For relations are not only interactions, but interactions that produce properties that are real, and measurable, only for those systems which are interacting. This is a particularly interesting notion of the reality of entities that pivots their existence and identity, one that even augments the philosophical bite of process thinking. Not only are individual entities precipitates of processes, as Rovelli would certainly agree, but some entities are individuals only within certain processes, while could not be such vis-à-vis other processes. The image of the universe one comes up with from a processual interpretation of Rovelli's physical theory is a vast set of processes—which do not form a whole precisely because of the suggested interpretation of gauge-variant quantities—giving life to individual entities that can be identified and isolated only based on an analysis of those processes.

5 Concluding Remarks

The present article aimed to show that, contrary to what one might *prima facie* expect, processualism can be squared with physical strategies that dispose of time as an absolute parameter. While for some physicists a processual view seems to be conditional on there being an absolutely identifiable process where entities enjoy a unique identity, this article explored a way to reconcile a genuine notion of process with relativistic physics and a recent attempt to combine it with quantum physics. I drew attention to Rovelli's relational account of canonical quantum gravity to demonstrate that it is consistent with processualism while successfully demoting time to the status of a gauge-variant quantity. On his view, physical processes are mapped in terms of interaction/correlation between physical systems. Based on this, a process is not something unique that evolves through time but is what happens to a given system while it interacts with other physical systems. As there is no absolute way to account for this interaction, so cannot the system's identity be uniquely defined. This type of timeless processualism is conducive to a revisionary theory of entities that substance metaphysics has long considered as self-evident, and in this sense, it legitimately falls within the scope of a metaphysical research agenda that is producing ground-breaking results on what it is that composes the world according to the sciences.

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