# Processes and Continuity: A Look from Quantum Gravity

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**Abstract:**

Process jargon is widespread in the physical sciences. Beginning with the work of Wesley Salmon, several accounts in philosophy of science have attempted to provide a definition of "process" compatible with scientists' understanding of causation and explanation. The proposed characterisation links processes to the properties of the spacetime they inhabit as regards continuity and genuine causality. Recent developments in theories of quantum gravity challenge the validity of process ontologies at the fundamental scale. In particular, this paper examines how arguments based on minimal length in the literature question the traditional definition of process. Process realism does not favour the processualist against these arguments. I conclude that certain theories of quantum gravity prevent a processual representation of the intended phenomena at the fundamental scale because they predict a violation of either the spatiotemporal specification or the causality conditions. In the end, the processualist faces a dilemma: either weaken the accepted definition of process without falling into substance ontologies, or hope that problematic theories of quantum gravity will be disconfirmed.

**Keywords:** Process, Continuity, Quantum Gravity, Quantum Spacetime.

## Introduction

Process jargon is common in the physical sciences. Many textbooks speak of "processes" in a very accommodating way: the process of condensation of a liquid; the process of discovery; the process of annihilation of a particle. The linguistic use of the term suggests that a process is, in essence, a transformation from an initial to a final state. Different processes differ in the specification of how this transformation takes place and what its characterising features are. For example, condensation involves a transition from one physical state to another, while discovery is generally conceived as a dialectical interaction between theory and experimental practice. Even focusing on *physical* processes alone raises an interesting philosophical question about how to characterise these processes: Do processes occur in space and time? Are they continuous or discontinuous? Are they observer-dependent?

Process philosophies typically approach these problems by looking for some interesting metaphysical characterisation. At their core, process philosophers try to make process ontology a viable alternative to the more traditional substance ontology, because the latter is perceived as too restrictive or misleading in certain contexts. This is the case in many investigations, both in Whiteheadian and non-Whiteheadian accounts.[2] Building on the work of Alfred Whitehead, the former conceive "actual occasions" as basic units resulting from the integration of processes of interaction and data transfer, whereas the latter, such as Sellars' and Rescher's accounts, take

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[2] Among the Whiteheadian accounts to philosophy of physics, see Bright 1958, Epperson 2004 and Herstein 2005. Non-Whiteheadians have initially focused on establishing some useful definitions of process in contrast with substance ontologies. For example, see Sellars 1981, Seibt 1990, Rescher 2000, Winters 2017. See also Seibt 2022 for an overview.

processes as basic entities with a specific way of happening or developing. Recently, process ontology has also been claimed to support metaphysical realism: "so long as one commits to the reality of an observable world, one must commit to the reality of processes. This is because our mere ability to observe is predicated on the existence of processes to enable and ground these observations" (Penn 2023, p. 1). By contrast, other philosophers of science have focused on the epistemological, rather than metaphysical, investigation into processes.[3] Assuming that the world is primarily constituted of processes, how can we understand or explain phenomena in these terms? In other words, the main concern is the epistemological advantage of processes over other contenders, such as tropes, entities, or events.

The flourishing research in quantum gravity (henceforth referred to as QG) solicits the epistemological question concerning the role of processes. It is unclear whether theories of QG allow phenomena to be represented in processual terms. That is, do these theories accommodate processual representation? Taking ontology in the broader sense of the domain of discourse of a theory, this question comes down to whether theories of QG can accommodate an ontology of processes (independent of any metaphysical realist commitment)[4] and, if they cannot, an ontology of "process-like stuffs" to be further characterised.

In Section 1, I provide a general definition of process drawing from the debate on explanation and causation in philosophy of science. Continuity and spacetime-dependence appear as two necessary conditions for the identification of processes as depending on the properties of an embedding structure. Modern physics suggests that this structure is scale-dependent. Section 2 argues that if continuity is forbidden in QG, processes cannot be continuous at higher energies, which contradicts the definition. Section 3 explores possible ways out of this argument. The lack of continuity requires the processualist to sacrifice crucial features of processes in order to preserve the others. Ultimately, the problem comes down to what distinguishes a process ontology from its alternatives.

I argue that those theories of QG that reject continuity cannot represent their domain of applicability in terms of processes. Processes are scale-dependent; moreover, they are constrained by the structure they inhabit (or constitute).[5] Insofar as theories of QG define this structure in such a way that continuity no longer holds, they prohibit processes from inhabiting it. In other words, some theories of QG do not offer a processual representation of phenomena. Instead, a possible process ontology must dispense with the continuity requirement. Whether this is the case or not has to be determined on a theory-by-theory basis.

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[3] This is the general attitude of process philosophers discussing about scientific explanation. See, e.g., Salmon 1984, Dowe 2000, Dupré and Nicholson 2018. On the possibility of using process philosophy to identify criteria for causal relations from an epistemological point of view, see, e.g., Hitchcock 1995, 2004.

[4] In fact, process philosophy is often formulated in terms of a metaphysical thesis: there are things in the world and they are processes. This is what I call the *process metaphysical realist thesis*. By contrast, a processualist might also argue for an epistemological thesis: our best theories describe the world in terms of processes (*process epistemological realist thesis*). If the processualist is not only a metaphysical realist, but also an epistemological realist, she will claim that processual representation brings our theory closer to an adequate description of reality. However, it is not necessary for the epistemological picture to match the way we think the world is. The process philosopher may be a process metaphysical realist, but still hold that our theories cannot and need not represent phenomena as processes in order to be true or empirically adequate.

[5] Some operational theories of spacetime, such as Reichenbach's 1969, suggest that spacetime is reconstructed from operations based on rods and clocks. A generalisation in terms of light beams and clocks can be formulated as a case for processualism: processes, and their interactions, would be constitutive of the spacetime structure, rather than the other way around. However, the following arguments are irrespective of the choice of one of the alternatives.

## 1. What is a process?

Processes are generally defined as non-particular, subjectless occurrents. As such, they are temporally extended (non-instantaneous), in the sense of flowing from a beginning to an end. They have measurable properties, so they can be empirically identified, but are not countable composites of more basic entities. They are also determinable, but not necessarily determinate. Processes are individuated by reference to the context to which they relate. Moreover, they are not changes, i.e., they do not properly have temporal parts, but rather can be divided into homogeneous parts for the sake of understanding (see Campbell 2015, pp. 73-79; 91-94).

For example, the motion of a billiard ball on a table is a process. The process of motion occurs over a period of time; it is extended in time and has measurable properties, e.g., a speed. The motion is continuous, determinable, and can be identified by the object of that action: in this case, the billiard ball. However, the occurrence of motion is independent of the specific object moving: it could just as easily have been a car or an ant. The motion takes place on a surface (the table). Finally, it cannot be divided into temporal parts, at the cost of falling into Zeno's paradoxes, but we can still identify homogeneous parts in order to follow it, for example the seconds in which it occurs.

According to Seibt's *General Process Theory*, processes are general, in the sense that they are not modifications of a particular entity or spacetime region. Rather, each process is multiply realisable, in the sense that it can be further specified or "realised:" the process "the activity *x* is happening" can be specified as "the activity *x* is happening right now", and even further as "the activity *x* is happening right now at this location" (see, e.g., Seibt 2018; also, Campbell 2015, p. 79-80). The specification of where, when and how the process occurs differently realises one same process-type. There are several ways of specifying a process: modal ("It's raining heavily"); quantitative ("It's raining a lot"); spatiotemporal ("It's raining in London right now"); etc. Spatiotemporal specification involves locating a process in spacetime, i.e., claiming that a process is happening in a particular place at a particular time.[6] The reference to the location of its happening allows processes to be associated with spatiotemporal properties, although strictly speaking they are not properties of spacetime: they simply happen in it, or inhabit it. As such, processes can happen in *any* spacetime region, but they are not bound to any *particular* region (as opposed to particulars, for example).

Philosophers of science have often been interested in the relation of processes to causality and explanation (see Dowe 2007): Under what conditions do processes play a causal role in observed phenomena? Do processes explain the production (or prevention) of certain phenomena?

Russell was one of the first analytic philosophers to consider the relationship between processes and causality. According to him, things are not persistent substantial entities, but rather sequences of events connected by causal relations. He writes:

> A "causal line," as I wish to define the term, is a temporal series of events so related that, given some of them, something can be inferred about the others whatever may be happening elsewhere. A causal line may always be regarded as the persistence of something – a person, a table, a photon, or what not. Throughout a given causal line, there may be constancy of quality, constancy of

[6] Up to some level of specification. Indeed, events are represented as spacetime points, hence processualists will likely avoid spatiotemporal specification of a process to blur the ontological distinction.

structure, or gradual change in either, but not sudden change of any considerable magnitude. (Russell 1948, p. 459)

According to modern metaphysics, this position would not be considered truly processualist, since the notion of process, or causal line, is defined in terms of other primitive entities, rather than being primitive itself (see, e.g., Campbell 2015, p. 94). Russell does however emphasise a crucial condition accepted by the following tradition. The quasi-persistence of things and their arrangement in causal lines justifies the introduction of the so-called *postulate of spatio-temporal continuity*: "when there is a causal connection between two events that are not contiguous, there must be intermediate links in the causal chain such that each is contiguous to the next, or (alternatively) such that there is a process which is continuous in the mathematical sense" (pp. 490-491).

Wesley Salmon adapts Russell's definitions to the distinction between truly causal and non-causal processes, or pseudo-processes (see Salmon 1984 *passim*; 1998, p. 16). He writes:

> There is a strong temptation to think of events as basic types of entities, and to construe processes – real or pseudo- – as collections of events. This viewpoint may be due, at least in part, to the fact that the space-time interval between events is a fundamental invariant of the special theory of relativity, and that events thus enjoy an especially fundamental status. I suggest, nevertheless, that we reverse the approach. Let us begin with processes (which have not yet been sorted out into causal and pseudo-), and look at their interactions […]. What we want to say, very roughly, is that when two processes intersect, and both are modified in such ways that the changes in one are correlated with changes in the other – in the manner of an interactive fork […] – we have a causal interaction. (Salmon 1977b, in *Id.* 1998, p. 135).

And, in another paper: "The main difference between events and processes is that events are relatively localized in space and time, while processes have much greater temporal duration and, in many cases, much greater spatial extent" (Salmon 1981, in *Id.* 1998, p. 286).

For Salmon, special relativity (henceforth, SR) is a paradigmatic example of a process theory (see e.g. Salmon 1984, pp. 140-141). He builds on a specific reconstruction of the theory dating back to Reichenbach (1969). In this approach, the spacetime structure is reconstructed from the intersection and evolution of light pulses, that is, of the fields that inhabit it. Light pulses are processes for the motion of free-falling bodies, and the light-cone structure determines the structure of spacetime. Causality is defined by the properties of lines in relativistic spacetime.[7]

According to Salmon, processes exhibit "a certain degree of uniformity" (Salmon 1984, p. 144). They are represented as *worldlines* in relativistic spacetime, with each worldline identifying the history of a given object, from its past to its future. The intersection of two worldlines identifies an event, i.e., a point in spacetime. Salmon's representation of processes as worldlines is based on Russell's *at-at* theory of motion: motion is defined as being located at precise points in space at precise instants in time, while movement is simply a correspondence between spatial positions and temporal instants. Processes must be *continuous*: "given two spatiotemporally distinct events in such a process, we can interpolate other events between them in the process" (Salmon 1975, in *Id.* 1998,

[7] For these *constructive approaches* to the structure of spacetime, see, e.g., Castagnino 1968; Ehlers, Pirani and Schild 1972/2012; Hayashi and Shirafuji 1977; Schelb 1996; Hehl and Obukhov 2006. Furthermore, see Adlam, Linnemann and Read 2022 for a critical assessment. Conversely, the *deductive approach* reconstructs spacetime geometry based on background logic and mathematical theories, endowed with suitable interpretation, whereas the field content is insufficient for its reconstruction. Some more recent references are, e.g., Andréka *et al.* 2010; Benda 2008; Cocco and Babic 2021; Madarász, Németi and Székely 2006; Mararász, Németi and Töke 2004.

p. 113).[8] If processes (causal and non-causal) constitute spacetime, then our physical theories must have sufficient mathematical power to represent a continuous spacetime structure. Conversely, if processes inhabit spacetime, then the mathematical structure must allow the representation of "enough points" so that all events in a process are located in spacetime. Local coincidences, i.e. intersections between worldlines, provide the underlying structure for a network of processes.

Some processes may also be causal. The identification of causality criteria is a long-standing problem in philosophy of science, to which Salmon has dedicated most of his work. Acknowledging that statistical relevance is insufficient to establish causality relations, Salmon's solution is to introduce a counterfactual procedure for modifying the properties of processes: the *method of marks* (see Salmon 1984, especially pp. 142-147). Marks are traits that are introduced into a process by modifying existing features. This modification occurs at the intersection between two processes (interacting fork), in which case both are modified. If the mark is transmitted along the process, then it proves that the process is truly causal. Transmission between two points, A and B, of a process means "being present in the process at every point between A and B without further interactions with other processes" (Salmon 1998, p. 21; see also *Id.* 1977a, in *Id.* 1998, p. 197). Continuity ensures that there are enough events between A and B, whereas propagation (or its prevention) depends on the specific nature of the process under consideration.

SR prohibits the causal propagation of information unless certain conditions are met. In particular, each system-observer is associated with a light-cone, i.e., that portion of spacetime traced by the light signals emitted by the observer. The interior of the light cone is the region of all its possible histories, with the lower cone being the set of past events and the upper cone being the set of future events. Worldlines that lie within the light-cone of a system are called *time-like*; those lying outside the cone are *space-like*; finally, those lying on the light-cone are *light-like* (or *null*). According to SR, only time-like or light-like worldlines are causal, i.e., those worldlines along which information travels at speeds slower than or equal to the speed of light. Therefore, there is a precise sense in which the spacetime structure prohibits some processes from being causal, insofar as they are specific kinds of worldlines: space-like worldlines are pseudo-processes, because they cannot transmit marks.

The spacetime-dependence of processes is made explicit by Dowe:

> A *process* is the world line of an object, regardless of whether or not that object possesses conserved quantities.[9] A process can be either causal or noncausal (pseudo). A *world line* is the collection of points on a spacetime (Minkowski) diagram that represents the history of an object. This means that processes are represented by elongated regions, or 'worms,' in spacetime. Such processes, or worms in spacetime, will normally be timelike; that is, every point or time slice on its world line lies in the future lightcone of the process's starting point. However, it is at least conceivable that the world line of an object may sometimes appear on a spacetime diagram as a spacelike worm. […] A process is the object's trajectory through time. […] Worms in spacetime that are not processes I call […] 'spatiotemporal junk.' Thus a line on a spacetime diagram

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[8] More recently, continuity has been defended by Dupré 2025 as a necessary condition for process ontology. As he puts it, "[a] process is always only partially and temporally stable […]. In fact, I define a process as requiring change for its continued existence" (p. 18). This suggests that, for Dupré, continuity is not confined to physical processes but also extends, for instance, to the biological realm. Given his definition, continuity becomes a defining feature of genuine processes.

[9] By "conserved quantity," Dowe means a physical quantity that is conserved along transmission and interaction processes. Conservation laws govern these quantities and allow them to be identified. Possessing one of these quantities means instantiating the corresponding property: a causal process depends only on a local property, i.e., the possession of a conserved quantity, without any influence from the rest of the universe.

represents either a process or a piece of spatiotemporal junk, and a process is either causal or a pseudo process. (Dowe 2000, pp. 90-91)

Dowe's account aims to correct the shortcomings of Salmon's criterion of mark transmission. Indeed, one of Salmon's main criticisms against conserved quantities was the treatment of *gerrymandered objects*, which possess a conserved quantity such as energy but do not transmit it. According to Salmon's theory, the worldlines of such objects are not causal processes because they do not *transmit* energy, but transmission is an unclear notion insofar as it involves circularity: causal transmission is defined in terms of marks, but marks are the traits that are transmitted. However, Dowe replies, the conserved quantity account cannot apply to such objects, because they are not classified as objects at all: gerrymandered "objects" are rather aggregates of different objects at different times, hence their possession of the conserved quantity is not *continuous* over time. As long as the quantity is possessed by the object along its worldline, it does not matter whether it is also *transmitted* from one configuration to another.[10]

## 2. Continuity in quantum gravity, or the lack thereof

According to the processual accounts in philosophy of science,

(P1) Processes are represented by continuous worldlines.

(P1) requires "enough" mathematical structure to represent each "piece" of the worldline, i.e., each event or sub-process that composes the worldline of the process under study. Continuity is understood as the possibility of transmitting or localising features, i.e., of (spatiotemporal) specifications of the process. As such, it is closely related to localisability: given a worldline in spacetime, continuity ensures that it is always possible to sharply locate the corresponding system at any point in the process, meaning that the process theoretically admits arbitrary specification. This point is the geometric representation of the configuration of the system, i.e., of the associated event, and contains information regarding its exact location.

Spatiotemporal localisation involves a measurement procedure: given an unknown initial position, we solve a localisation problem by controlling a finite set of parameters (e.g., the initial state of a probe and background environmental conditions) and by producing an appreciable variation, i.e., by making a probe interact with the target. By varying the properties of the probe, information about the properties of the target (in this specific case, its spacetime location) can be recovered. Localisation therefore requires interaction, such as scattering or variation of a probe field, as well as the ability to access relevant information about the pre- and post-interaction state of the probe.

Among the possible processes, some involve causality. In particular,

(P2) Causality is related to the spacetime structure, in particular to the light-cone structure.

(P2) requires an adequate notion of causality that is compatible with the constraints imposed by SR. The speed of light is the characteristic invariant quantity of SR and imposes a bound on the propagation of information. This bound extends to quantum theories as required by quantum field theory (QFT): the microcausality condition on field theories prescribes that correlation between two fields is forbidden if their sources are space-like separated, implying that no superluminal

[10] Notably, in 1997 Salmon himself accepted conserved quantities as a causality criterion, while still preserving the transmission scheme. He writes: "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" (p. 468).

communication is allowed at the quantum, as well as at the relativistic level. The light-cone structure is based on the postulate of invariance of the speed of light, so our ability to theoretically define causality in terms of time-like or null influence ultimately requires that one be able to define a light-cone structure before establishing causal relations.

General relativity (GR) and quantum mechanics (QM) already raise some concerns about the viability of (P1-2) as adequate conditions for the definition of processes. Quantum discontinuities (e.g., quantum jumps) have often been raised in the literature as counterexamples to the existence of processes at the quantum level: atomic interactions are not genuine processes, because (P1) is violated by the particles involved. (P1) is also threatened by GR, as the latter admits singularities, i.e., regions that are removed from spacetime. Singularities usually (but not necessarily, see Curiel 1999) involve geodesic incompleteness: geodesics, i.e., trajectories of free-falling observers, would cross a singularity, so that the observer would disappear out and reappear into existence. Incompleteness violates (P1), so either the processes are never geodesics (which is very hard to believe), or they might not be continuous. Moreover, causality is a rather difficult concept to define in GR, so the ability to assess (P2) is in question. Thinking of processes as directed from an "initial" to a "final" state conflicts with the existence of closed time-like curves in spacetime, which correspond to cases of backward causation. But if backward causation is admissible, then there is no trivial definition of the orientation of the propagation from one event to another along a process.

Quantum gravity inherits the above concerns from relativistic and quantum theories. A theory of QG should provide a unified framework for both theories in their respective regimes of applicability. Moreover, it should provide new physics in inaccessible, high-energy regimes. In particular, it is common (though controversial) to assume that gravity behaves in a quantum (or at least non-classical) way at high energies, in which case the standard relativistic description would break down and a new theory would be needed. Such regimes, although technologically inaccessible, raise further concerns about the adequacy of a process ontology for theories of QG. These theories deal with the time coordinate in original ways, ultimately falling into the so-called problem of time. The absence of a temporal evolution in theories such as loop quantum gravity conflicts with the existence of processes as occurrents (see, e.g., Margoni 2022 for a defence of processualism against the problem of time).

A processualist attempt at a theory of QG might introduce processes as inhabiting quantum spacetime.[11] Thinking of these processes as being variations of quantum fields or motions of particles does not make much difference. Rather, the main problem is whether such a quantum spacetime is favourable for these processes to exist, i.e., to be defined. The properties of quantum spacetime will obviously constrain the properties of the processes that inhabit it. Therefore, rather than simply translating the classical framework from relativistic spacetime to quantum spacetime, it is reasonable to expect some challenges.

To illustrate, continuity characterises the structure of relativistic spacetime. Suppose that GR admits a processual representation of phenomena, and suppose that one extends its regime of applicability to arbitrarily small scales. In other words, suppose that spacetime is continuous at all

[11] In order to make my point here, I will be very accommodating and welcoming to processualist accounts, in that I will concede them to be able to overcome most controversial points. For a starter, I will agree with them about the problem of the existence of extremes in a process. Most processes have undefined extremes, i.e., non-sharp beginning and ending. However, it is often possible to establish (possibly as a matter of convention) a starting point and an ending point, although somehow arbitrarily: what matters is whatever happens in the middle. Moreover, there are processes to which the problem of the extremes does not apply. For these reasons, I will assume that the extremes can always be identified, for difficult cases do not undermine the processualist attempt.

scales, especially at high energies, so that processes are definable. Quantum physics holds in these regimes. One goal of a theory of QG would be to describe how relativistic and quantum phenomena coexist and relate to each other at these scales.

Continuity implies that localisation is possible, but several arguments show how the incompatibility between GR and QFT in high-energy regimes implies the impossibility of sharp localisation beyond a certain bound. For example, consider a target of unknown location, say at an unknown point within a region of finite radius, and try to find its position along a coordinate axis of the chosen reference frame. This measurement can be carried out using a suitable probe, with known initial state, which we can detect at the end of the procedure.

In this regime, QM is relevant, so the probe is affected by uncertainty relations: maximising the precision of the localisation of the scattering between probe and target increases the momentum uncertainty of the probe. This momentum uncertainty is transferred to the target and concentrated in the localisation region. Because of the increase in the energy of the target, GR predicts that its energy-momentum tensor will generate a stronger gravitational field: the more one tries to minimise the position uncertainty (i.e., to sharpen the position measurement), the stronger the gravitational field will become. As a result, the gravitational energy reaches the point where a mini-black hole is formed, so that information about the position of the target cannot escape its event horizon to reach the observer (see Doplicher, Fredenhagen and Roberts 1995).[12] Therefore, to maintain GR at this scale, and thus spacetime continuity, is to defeat its very own physical meaning. Spacetime cannot be continuous, because point-wise localisation makes no physical (other than mathematical) sense. *A fortiori*, worldlines and the processes that inhabit it cannot be continuous. Insofar as (P1) is based on the continuity assumption of GR, it is untenable at the fundamental level.[13]

A strict processualist might object that this argument is ill-posed: there are no individual probes and targets, but rather processes. Specifically, instead of talking about the probe and the target, one should talk about the process of interaction between the two: location results from this interaction, whereas before one could distinguish two processes, the first understood as "a probe moving in spacetime with some momentum" and the second as "a target at rest at some unknown point in spacetime". However, refining the picture of the above experiment misses the point. Non-localisability, and hence lack of continuity, do not arise from the nature of our ingredients, be they processes or particles, but from their interaction. Even if we speak of the process of interaction, i.e., of the intersection between two independent processes, the question remains: Where does the interaction take place? Since the location of the interaction is the same as the location of the target (equivalently, the location of the process interpreted as the state of the target), the location of the target remains indefinable. Reframing the problem in strict processualist language does not solve it.

Several theories of QG conclude that fundamentally there are only "atoms of spacetime," i.e., some minimal building blocks contrasting with the continuity of field quantities. For example, this is the case of many graph-based approaches, such as group field theory or loop quantum gravity, or algebraic approaches such as noncommutative theories of gravity.[14]

[12] This argument is also similar to Bronstein 1936, which highlights the conclusion further.
[13] Notice that this argument (and other variations) can be circumvented in various ways. See, e.g., Kiefer 2007, pp. 18, for some suggestions.
[14] See Hossenfelder 2013 and references therein for a map of the approaches based on a minimal length or area.

Furthermore, quantum gravity often takes the lack of localizability in terms of fuzziness.[15] The main analogy is with quantum mechanics: given two incompatible quantities, the trajectories in the phase space spanned by a basis of their eigenstates are fuzzy, because the state is described as a combination (superposition) of possible outcomes of the measurement of each quantity. In other words, the state is represented as a probability distribution over phase space. The challenge to continuity intersects with the suggestion that fuzziness may also be a feature of quantum-gravitational phenomena. The argument, first proposed in Mead (1964), uses a slightly modified version of the previous setup.

Consider a Heisenberg-microscope-like setup: a target is located at an unknown position within a region of fixed radius; a probe (e.g., a photon) is prepared so that its initial state is known; a lens or detection plate is placed above the target, so that information conveyed by the interaction radiation can be registered. Localisation is achieved by means of the scattering between the probe and the target. Suppose that the experiment is carried out in the same high-energy regime as the previous one, so that both general relativity and quantum physics are relevant. Increase the energy of the probe to minimise the spacetime uncertainty and maximise the resolution of the position measurement of the target. As a result of the scattering, radiation is emitted in the direction of the lens, with a specific amplitude conveying the position information. However, the more energy that has been transferred from the probe to the target, the more the radiation will pull the target along its direction of propagation, adding a new term to the overall position uncertainty and defeating the purpose of the procedure.

A possible response would be to repeat the experiment using particles of a different nature. However, it can be shown that the resulting uncertainty is *universal*, in the sense that it does not depend on the specific nature of the particles involved, but only on the gravitational force they exert. Therefore, the total uncertainty affecting the reading of the detection plate is fundamental in this framework: at high energies, the position is *fuzzy*. It can be shown that a minimum uncertainty describes a corresponding minimal length, beyond which these effects are dominant. Since (P1) represents processes as worldlines crossing regions of size smaller than this fundamental length, fuzziness will prevent sharp definition.

In fact, consider two processes that are arbitrarily close to each other, e.g., in the region immediately before an interaction takes place. According to the traditional account, it is always possible to distinguish each process by its respective position. However, in minimal length scenarios, if the distance between the two processes is less than this length, then the distinguishability criterion based on relative location fails. According to the theory, the region is not occupied by two distinct processes. Rather, it contains a family of *possible* processes. The limit prevents the determination of one possibility over the others, so the distribution of processes over the region cannot distinguish between its possible realisations.[16]

Furthermore, certain spacetime models imply that only those worldlines associated with zero velocity systems are sharp. This is the case of noncommutative spacetime models (see e.g. Ballesteros *et al.* 2021). Assuming that this worldline is that of an observer (since each observer is at rest in its

[15] This usually follows from the introduction of a superposition principle for the gravitational field, such as in the case of canonical gravity or loop quantum gravity.

[16] In the context of a quantum theory, this certainly echoes the debate between supervaluationism and determinable-based account. According to the former, fuzzy processes stand for families of possible realisations, i.e. single, well-defined processes which can be realised inside the minimal region. This possibility conflicts with the role of a minimal length, as defined above. Instead, a (gappy) determinable-based account allows fuzzy processes to be the object of discourse without need of any higher-energetic realisation.

own reference frame), this means that any other worldline will exhibit some degree of fuzziness proportional to its distance from it. In particular, the intersection picture of the low-energy regimes does not have a natural translation at the high-energy level: high-energy processes cannot intersect due to fuzziness. In fact, the point-wise intersection will be within a region of minimal size, so there is a non-zero probability (governed by a so-called *impact parameter*) that the two processes come extremely close but never actually intersect. The fuzziness of the intersection is at odds with Salmon's picture: if processes cannot intersect (or rather, if we do not have precise control over the intersection, but only some probability of success), then the criterion of transmission of marks becomes questionable, as it loses applicability.

Finally, fuzziness also affects the light worldlines (see Ballesteros *et al.* 2022). This means that the boundaries of the light-cone, i.e., the null hypersurfaces, are no longer sharply defined. As a consequence, the more the speed of signal propagation along a process approaches that of light, the more uncertain its causal character becomes, for it may be that violations of relativistic causality occur. In fact, causal ambiguity follows from the blurring of the distinction between time-like and space-like worldlines, where formally this distinction depends on the identification of light-like separating surfaces. Since (P2) is based on the ability to sharply define a light-cone structure, even this second feature of traditional processes must also be reconsidered at the fundamental level.

## 3. Are there processes at the fundamental level?

Examples from modern physics suggest that spatiotemporal specification is a relevant feature for the processualist to explore: What are its bounds? What is its epistemic relevance? Processes are highly sensitive to spacetime structure: insofar as they can be specified in spatiotemporal terms, processualists must ensure that the spacetime structure is compatible with relevant, traditional processual features, at the cost of indefinability. The more specific the location, the smaller the scale at which the process is supposed to occur, and thus the greater is the risk of quantum gravitational effects screening off information. Theories at different scales will assign different structures to spacetime, and thus represent spacetime as scale-dependent. Scale sensibility therefore makes the spatiotemporal specification of a process somewhat tricky.

The literature suggests that a process ontology in the quantum regime might be controversial. Thinking of fields as processes has the clear epistemic advantage of making their dynamics more intelligible, but it is not the only known option, nor is it possible to trace a line of consensus on the ontological interpretation of QFT (see, e.g., Seibt 2002, Kuhlmann 2010). Any field theory on quantum spacetime will certainly inherit and exacerbate these problems. Nevertheless, for the sake of the argument, assume that the processualist can resolve the situation in her favour. I will concede to the processualist that the world is primarily made up of processes, and that our low-energy theories successfully represent this ontology in processualist terms without much difficulty.

In this section, I argue that despite the process metaphysical realism, the processualist ultimately fails to capture quantum gravitational phenomena in terms of processes, and that her only way out is to change the very same definition of process. In other words, despite process metaphysical realism, process *epistemological* realism is prone to failure in specific theories of QG. In particular, I present two main arguments against the attempts of the processualist. A first argument counteracts the attempt to correct the representational capacity of the theory based on a realist assumption, by showing how it ultimately misses the point of contention. The second argument questions the possibility of obtaining the same processualist conclusion by invoking the concept of emergence, and

I argue that the main assumption of the processualist either leads to circularity or cannot reach the desired conclusion. Finally, I illustrate how the last hope for the processualist, i.e., retaining a causality criterion based on SR, is also challenged by the non-classical behaviour of quantum spacetime according to several theories.

### 3.1. Process realism and correlations

Theories of QG question whether the processualist picture can be extended to arbitrarily small scales, i.e., to higher energies. In other words, what is the ontology of field theories at the fundamental level? Can processes be defined on quantum spacetime? As discussed above, certain theories suggest that continuity must be rejected at quantum-gravitational scales. Since there is no evidence that favours one of these theories over its rivals, it is doubtful whether these arguments can be trusted in an ontological assessment. Therefore, either these theories excluding continuity will turn out to be wrong, in which case traditional processualism still has a chance to succeed at the fundamental level without too much adaptation; or, these theories will turn out to be correct, in which case processualism faces a real challenge.

For the sake of the argument, consider the latter scenario. The absence of continuity implies that no variation is defined within a region of minimal size. Any such variation would be undefinable by the theory, in the sense of being physically irrelevant at the scale under consideration. Nevertheless, processes are continuous, which means that they are traditionally defined at each stage. Minimal regions prevent any stage from being defined unless it involves a variation at a scale larger than or equal to the minimal spatial and temporal bounds. Since these regions cover all spacetime, and thus the entire process from beginning to end, no process is strictly speaking fully definable unless it is "sufficiently macroscopic." Nevertheless, something does happen, whether it is definable or not.

Consider, for example, the case of photon scattering in so-called noncommutative theories of spacetime (see Hewett, Petriello and Rizzo 2001). Specifically, consider the case of a fixed coordinate system characterised by time-space noncommutativity, meaning that the time and space coordinate functions do not commute. Take two photon beams moving towards each other until they collide (i.e., they Compton back-scatter off incoming fermion beams). The collision results in the creation of a new photon-photon pair. However, the phenomenon does not occur in the centre of mass frame as expected. Furthermore, according to the noncommutative theory, it is expected to display "exotic" new features, such as the violation of Lorentz invariance or a dependence on the azimuthal angle of the scattering, which are absent in standard quantum electrodynamics (QED).

It is possible to think of this phenomenon in terms of processes: we have two incoming processes, corresponding to the motion of the two photons; an interaction between the two photons; and two outgoing processes, corresponding to the motion of the resulting photons, respectively. In order to explain the unusual behaviour, one needs to introduce a noncommutative spacetime structure. However, as a result, the point of interaction cannot be defined in noncommutative spacetime, since the theory deprives any region of size smaller than the Planck length of its physical meaning. Therefore, there is no way to identify the processes under investigation with sharp worldlines. Nevertheless, we can see that something has changed: the head-on collision of photons has produced a new photon-photon pair in the scattering.

At this stage we should resist the temptation to see the above setup as a case for processualism. At the very least, the scattering scenario shows that there is some *correlation* between the energy and motion of two incoming photons and the production of two outgoing photons with new properties. This correlation allows us to say that something has happened, that something has changed with respect to an initial configuration: if the two photons had not collided at the appropriate energy, the new pair would not have been produced, at least not by this process. Although the specific interaction between the photons is inaccessible to the noncommutative theory, the results are quite noticeable.

A hardcore processualist might not be satisfied with mere correlations. Even though the theory prevents a processual representation of the above experiment, she can still question the applicability of such a theory to the case at hand. In other words, processualists can still argue that the observed change indicates the existence of an underlying process on metaphysical grounds, and that the lack of processual representation in our theory is not enough to exclude its postulation.

Indeed, epistemology need not constrain ontology: theories need not guide our ontological commitment (*pace* Carnap). This would be the case with process realism at the fundamental regime. A proponent might argue that to allow a theory to prevent processual representation is to accept a certain degree of mismatch or misrepresentation in our conception of the world at the scale under consideration.

However, the adequacy of our theories in terms of what we think the world is like also depends on their representational power. Specifically, if we accept the epistemological-ontological mismatch, then theories that exclude continuity can be consistent with process ontology, but they will lack detail. The processualist can be challenged by asking: What are the specifics of this process? The answer depends on the *resolution* (or *fine-graining*) that the theory allows within a given regime. Continuity allows sections of the process to be specified down to an arbitrary resolution. Lack of continuity means that the resolution is limited from above. In the latter case, the processualist can still commit to processes as an ontological justification for the correlation represented by the theory, but she will not be able to specify *how* the process happens.

Moreover, an opponent might point out that processes are not just correlations, but are supposed to do much more than just correlate. Unlike mere correlations, processes are often intended to identify a link (even a cause) between the two endpoints, or any two points in the middle. Correlation is better suited to substance ontologies. In this case, one can consider two entities, each of which has a certain characteristic, let it be A for the first entity and B for the second. A correlation between A and B could be formulated as follows:

(C) Whenever the first entity has A, the second entity has B.

(C) certainly has descriptive power, but it does not explain much: why and how does the occurrence of A contribute to the occurrence of B? Explaining B in terms of A is likely to require stronger epistemic information, for example about the way in which B occurs under certain circumstances. In this case, correlation does not tell us enough about the *why* and the *how*, only *that* B occurs provided that A does. Processes are supposed to fill this epistemic gap by interpolating a causal chain from A to B. Thus the processualist cannot be satisfied by simply taking correlations to equate processes, for she would be trivialising one of the very reasons why she committed herself to a process ontology in the first place, rather than one of substances.

Ultimately, the problem is one of representation, so the process realist simply misses the point of contention. Certain theories prevent us from knowing how hypothetical processes develop (i.e., happen), but they do not exclude the possibility that there are processes out there in the world. In a certain sense, processualism is still a viable option, especially for the anti-realist. However, it also retreats from its original role as an alternative to substantialism because it loses one of its advantages, namely the fact that processes interpolate steps between two correlated events. In the light of certain theories of QG, no specification can be given beyond the mere establishment of a correlation.

### 3.2. A top-down processualist argument

The processualist may still have a second chance to counter the argument against localisation. Fundamental theories must accommodate standard physics in overlapping regimes, in this case at lower energies. Insofar as the processualist can find sufficient representational power for her project in the standard theories of low-energy physics, she can retain this picture while limiting its scope. She can restrict process realism to low-energy scales, and suggest that fundamental processes *emerge* from a non-processualist fundamental ontology. Then she faces a new challenge: to show *how* the reduction takes place. From the point of view of representation, this means showing how a processual representation emerges from a non-processual, more fundamental one.

It is important to specify here what I mean by emergence of fundamental processes. The notion of emergence is indeed largely discussed in philosophy, and especially in philosophy of physics.[17] In this section, I use "emergence" in the sense of derivation of novel and autonomous features of low-energy phenomena and systems from high-energy physics. This very broad understanding of emergence is compatible with QG and does not conflict with the notion of reduction.[18] Specifically, in assessing the position of the processualist, I am interested in the emergence of an ontology of processes from an unknown, more fundamental ontology, according to the description provided by our most successful or promising theories. Conversely, I will not assume any further specification of "emergence," "novelty" or "autonomy." Indeed, I believe that the argument and its analysis can stand irrespective of such specification.

In light of this, the processualist might even be willing to go further. Process realism at lower energies opens a gap between ontological levels. By *ontological levels* I mean the ontological catalogue associated with each energy regime according to our metaphysical stance. The processualist might question the correctness of such a divide: Are we sure that the fundamental ontology is really non-processual? Low-energy process realism raises this question as a way of bridging the ontological gap between levels.

A way out of this new challenge might be to force processualism to high energies because of a representational deficit of the theory with respect to the metaphysical scenario. The argument, which I call the *top-down processualist argument*, is as follows:

1. Consider a variation of a physical setup involving a high-energy phenomenon.
2. Assume that there are processes at low energies.
3. In particular, there is a low-energy process that corresponds to (explains?) the high-energy variation.

[17] For a presentation of the main problem of emergence in QG, see e.g. Wüthrich 2018 and Crowther 2022.

[18] Crowther 2018 even suggests that theories of QG tautologically satisfy weak emergence, if they are well-defined.

4. Assume that the world is structured in a hierarchy of processes, i.e., that low-energy processes emerge from finer-grained high-energy processes (*hierarchy assumption*). [19]
5. Then the high-energy variation is not just a correlation, but a process.

The argument rests on the crucial hierarchy assumption. Postulating a hierarchy means extending the process ontology to arbitrary scales. Each scale will represent different processes up to different levels of specification, because the process ontology is closed under specification (up to reasonable limits). Therefore, it is possible to explain the high-energy correlation in terms of an underlying process by extending the low-energy process realist assumption.

I contend that the hierarchy assumption fails to support the case of the process realist for two reasons. Firstly, in order to derive 5, the advocate of process emergence must be implicitly committing to the conception of *weak emergence*. If processes weakly emerge from an underlying ontology, it is possible for the latter to be of the same kind of the former, namely, processual itself. Instead, if the relationship between ontological levels is one of *strong emergence*, the emergent, low-energy level ontology displays new features that are not reducible (in the standard philosophical jargon) to those of the high-energy ontology. Consequently, it would be reasonable to expect a mismatch between the two ontological levels, thus admitting that the emergent, low-energy ontology consists of processes, whereas the underlying, high-energy one does not.

Secondly, the arguments leading to the rejection of continuity at high energies contrast with the definition of high-energy processes implied by the hierarchy assumption. Taking this assumption as a reason to revise our physical results would not amount to a justification for the assumption itself. Physics cannot support the hierarchy assumption at the cost of circularity. In fact, several candidate physical theories in QG do just the opposite.

An alternative way to support the assumption would be to accumulate a sufficiently large number of cases of successful process description at low energies. In particular, let all these cases be independent of any reference to fundamentality. Then the top-down argument works as an inference to the best explanation: it makes the case for a fundamental process ontology based on the large evidence of successful processual representation at low energies. For we have no other access to the high-energy regime than a theory with representational deficiencies, while we have many neighbouring cases going in the direction of process ontologies, thus making it unlikely that anything in the ontology would change with scale (unless strong emergence is considered). However, this modified top-down argument would still be unsatisfactory or even controversial. The only support for the processualist is that it is *reasonable* to conclude that there are processes fundamentally, because low-energy processes must somehow emerge. However, the large number of successful cases which support the hierarchy assumption does not *entail* that the only possible scenario must involve processes and no other alternative.

### 3.3. Against the demarcation between causal and non-causal

The lack of continuity seems to corner the processualist. However, she can still take advantage of the situation by turning the problem in her favour. Traditionally, events in relativistic theories are

[19] This assumption is widespread in processualist approaches to the philosophy of biology: see Dupré and Nicholson 2018. A reasonable extension to the realm of physics can be extrapolated from their assessment of quantum field theories: "what contemporary physics seems to be telling us […] is that the basic ontological constituents of the universe are not elementary particles […], but fields extended in space-time. Though we are not entirely sure whether fields are either processes or things, they do appear to me more like the former than like the latter" (p. 15).

represented as spatiotemporal points. However, the lack of continuity implies that a minimal spatiotemporal extension should be considered, in the sense that no point can actually be defined in such a theory. Then one either removes events from the ontological catalogue or changes their characterisation. *Extended* events may be a favourable option for the processualist. Indeed, from a processualist point of view, events are defined in terms of intersections of processes. But interactions at the fundamental level cannot be instantaneously and pointwise localised in space, so they have to be conceptualised as *processes* of interaction. It follows that since events cannot be point-like objects, they must also have non-zero duration and extension. The elimination of spacetime points allows the processualist to remove instantaneous events from the picture, while allowing for a minimal scale as a bound for extended events. This means that interaction events can be specified up to a limit beyond which the theory is unable to describe or explain their dynamics.

Recall that some theories of QG predict nonlocal behaviour at the fundamental level, in the sense that they allow the propagation of signals at a distance (see Hagar 2014). Specifically, given a region of minimal size, a signal travels faster than light from one side of the region to the other. No variation is defined within the minimal region (i.e. at a finer level of description), so any propagation effect within it must be irrelevant to the coarse-grained effect under investigation.

The processualist can accept both an extended picture for interaction events and a fundamental theory of causality. However, nonlocality means that the maximality of the speed of light breaks down at the fundamental scale, according to some quantum spacetime models. For example, in Salmon's picture, an interactive fork involves marks travelling from incoming to outgoing processes. In this case, nonlocality means that propagation into and out of the interaction region occurs at a speed faster than $c$, violating the causality criterion. As a consequence, the distinction between causal and non-causal becomes blurred.

More specifically, the light-cone structure loses sharp boundaries, so that the speed of light is not a good demarcation criterion due to fuzziness (*pace* Salmon). Fuzziness introduces a degree of uncertainty about the causal nature of the process: if the process allows transmission at a speed close enough to that of light, there is a non-zero probability that the transmission violates the relativistic bound, i.e. the process has a non-zero probability of being non-causal.

Finally, marks are introduced by interaction. In particular, the method of marks, as described by Salmon, is a counterfactual procedure involving an interaction with the process under study: the process is causal if, *assuming* that an interaction takes place, the resulting mark *would be transmitted* along the process at a speed less than $c$. The processualist must take on the burden of specifying how counterfactual or interventionist criteria can be reconciled with nonlocality.

The upshot of the nonlocality problem for processualism is the following dilemma. Either the processualist maintains her traditional criteria and claims that there is no causal process at the fundamental level, since all processes violate the constraint on the speed of propagation. In this case there can only be non-causal processes at the fundamental level. Or the processualist can abandon the traditional criteria as unsuitable for fundamental regimes. In the latter case, it does not make sense to draw a causal-non-causal demarcation at that level, because these processes avoid any attempt at interaction, such as the method of marks. However, she must then find new criteria.

## Conclusion

In this paper, I have argued that the traditional definition of process is ultimately untenable at the quantum gravitational level. Several theories of QG reject continuity, which is however a necessary condition for defining a process. The lack of continuity implies that processes become “gappy,” introducing an inevitable degree of unspecification (or lack of resolution) proportional to the minimal uncertainty of the spacetime the process inhabits. This suggests that these theories cannot represent a process ontology unless the very same definition of process is weakened in some way. It is therefore the task of the processualist to assess which ingredients to retain, while preserving the core differences between processualism and competing ontological accounts.

It is striking that in recent decades operationalist philosophy of physics has explored a number of definitions of process that are quite different from the traditional ones. According to these accounts, processes are correlations between measurements performed in spatially and temporally distant laboratories. The idea of information propagating from one point to another becomes that of a correlation between measurement results. Causality is established as a partial order between these results (see e.g. Adlam 2023). While it is not the purpose of this paper to argue that these approaches are better suited to some theories of QG than the traditional ones, it is interesting to note how correlations can be reconciled with an extended, more accommodating notion of process.

Processes need not be continuous. Ultimately, the possibility of having a fundamental ontology of processes comes down to two questions: which theory of QG will ever turn out to be correct in the distant future, and what the processualist is willing to sacrifice.

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