Original Articles

PURE PROCESS REALISM: THE UNIFICATION OF REALISM AND EMPIRICISM

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Abstract: I describe the key features of pure process realism—realism about the processes that are identified by experimental dynamics structured by scientific models—showing that the view meets criteria for scientific realism. I argue that process realism resolves many of the worries of the antirealist, including the problems of idealization, underdetermination, contextuality, multiplicity, and the pessimistic meta-induction. I show this resolution in the context of a contentious model from physics: the Bohr model of the atom. I then generalize from this discussion to a collection of upshots and constraints on process realism as a view, in order to further distinguish it from orthodox, substance-paradigmatic- or thing-realism. Therefore, pure process realism is shown to be a form of realism compatible with empiricism.

[1]: Introduction

I argue that pure process realism (Penn 2023) resolves the perennial debate between scientific realism and antirealism. The process realist contends that there can be no experiments, observations, interventions, etc. without processes. These experimental dynamics in turn act as identifiers for processes within systems of study, described by the scientific models that are used to structure those experimental dynamics. Thus, process realism treats as real only those elements of empirical and modeling practice that are essential to that practice. Moreover, process realism offers a novel argument for realism divorced from variants of the no-miracles, explanatory success, and robustness arguments of orthodox realism. As a result, process realism does not commit to the extra-empirical metaphysics that has troubled antirealists for decades, i.e., thing-like or substance-paradigmatic metaphysics.[1]

To show this, I argue in section 2 that process realism is indeed a fecund metaphysics to satisfy the realist. In section 3, I show that the historical worries of the antirealist offer an inductive basis for rejecting non-process metaphysics, i.e., the substance-paradigm. These include worries about idealization, contextualism and pragmatics of model use, and the pessimistic meta-induction. Finally, I show in section 4 that the process realist resolves these worries. I first consider a contentious model—the Bohr model of the atom—and extract a collection of upshots and constraints for process realism. I show that these constraints enable process realist approaches to make realist metaphysics compatible with empiricist epistemology. Put simply, process realism presents a truly novel approach to scientific metaphysics that

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[1] Ladyman and Ross (2007, Ch 1, p. 7) also call this metaphysics the neo-scholastic metaphysics.

reframes the realism debate to support and unify contemporary philosophy of science.

[2]: Process Realism and its Realism

[2.1]: The Structure of the View

According to pure process realism, described in Penn (2023, Ch. 1), scientific models[2] identify processes in the world. More specifically, scientific models identify all and only those processes that appear as dynamic participants within our experiments, interventions, and observations. Drawing on the ontological framework of the General Process Theory (GPT),[3] Process realism does not define processes,[4] but categorizes them in terms of the features by

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[2] Note, I refer to models as opposed to theories throughout this discussion for two reasons. First, models carry less structural or semantic baggage than do theories. We might think of a theory as a special kind of model (e.g., a model of models), or else as a model that has achieved sufficient complexity, structure, scope, or some other virtue. Even if we think of theories as different in kind from models, we should nevertheless maintain that models play an essential role in the operation of a theory. Second, models are the locus for contemporary discussions in philosophy of science (with the notable exception of realist literature, in which many works still talk of theories).

[3] See Seibt (1990, 1995, 1996a-c, 2004a-b, 2007, 2009 especially 2010, 2015, 2018). Notably, the GPT is distinct from Whiteheadian process ontology, even though they share many similarities, and makes good on the promise of Sellars (1981).

[4] It should be noted that no ontological primitive is amenable to definition. Things, objects, structures, etc. are equally slippery

which we identify them. The relevant features are collected here:

(1) Processes are distinguished from other types of entities by…

- (a) Processes are *general*, not particular entities. Identifying a process does not inherently locate it. Processes become localized (where possible) by constructive context and measurement, not by internal character.
- (b) Processes are *subjectless*, neither alterations of things nor dependent on the existence of underlying things to carry or engage in them (i.e., vehicles/subjects).
- (c) Processes are *occurrent*, not continuant, temporally extended such that they cannot be identified instantaneously.
- (d) Processes are measurable, not countable. They have no identity that allows them to be named or listed, but can be identified through dynamic acts such as measurement.
- (e) Processes are *determinable*, not determinate. They are not defined, and have no definite identity, but are identifiable through epistemic/practical activities.
- (f) Processes are *contextual*, not independent/isolated, such that no process can be identified without identifying its dynamic context. Isolating a

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entities. A process ontology is in parity with other ontological pictures in this regard.

    process involves activities performed to enact this isolation.
  - (g) Processes are not state-based differences, or changes, or stages, but can have functions measured by, or partitioned into these.

- (2) Processes have participant, not part-based mereological structure. I.e., one process is distinguished from another by…

  - (a) Which systems the process participates in.
  - (b) How a process participates in a system, or its dynamic context.
  - (c) How a process is said to manifest internal participant features, or how it relates to other processes, as in, e.g., cycling, sequencing or following, forking, converging, or other dynamic shapes.
  - (d) The degree to which a process is like-parted.

With these, we have a list of identifying features by which we can determine (1) that an entity is a process, and (2) that it is relevantly different from another process. The contrastive alternate features corresponding to any of the above are what (partially) define the "substance paradigm."

These features enable processes to be identified in scientific models in the following way. First, processes never have identity, but instead are only ever identified. I.e., we measure and interact with the world, and these activities are what allow us to recognize similar processes. This forms the basis of the process realist's commitment. Namely, a process is identified with a collection of measurements, experimental interventions and controls, observations and controls, and other activities to form a complex dynamic context. This dynamic context then identifies the internal system processes as those that are continuous participants within this dynamic complex. The diagram below depicts the sketch for how this works (figure 1):

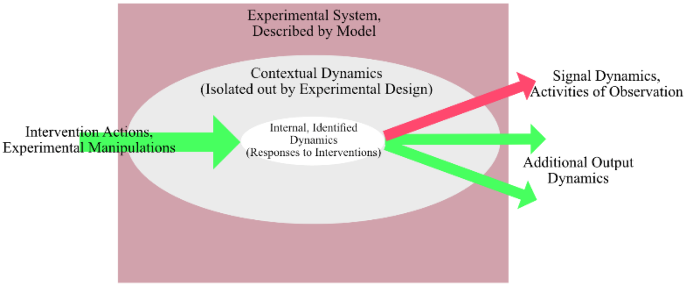

Figure 1: A sketched depiction of the various parts of an experimental system, and the location of the identified dynamics to which the process realist commits.

[2.2]: An Illustration.

As a specific illustration of the above, consider a candle flame.[5] A candle flame is not substance paradigmatic: it is not object-like, a continuous stuff, a structure, an essence, etc. Importantly, this is not a philosophical result, but a scientific one: following Becher and Stahl's attempts to describe fire and flame in substantial terms, investigations into the scientific implications of their phlogiston account showed significant empirical consequences ruling against the account. These results are collected perspicaciously in Faraday's (1848) lecture series on the chemical history of the candle.

Instead, the candle flame is characterized by a collection of processes, the dynamic equilibria of which produce stable systemic features. For example, the shape of the candle flame is the stable balance of convection currents, heat flux from the combustion zone, incandescence, radiative melting and capillary motion of paraffin, and air flow around the candle. These processes produce a cylindrically symmetric balance, and the disturbance of any one of these disturbs the shape of the flame.[6]

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[5] This example is described thoroughly, with more historical nuance as well as extended arguments for the processual interpretation, in Penn (2023, Ch 3).

[6] One might object that the candle flame is still metaphysically defined by substrate particles. Two responses are available to the process realist on this point. First, there is no reason to suppose that molecules, atoms, candle wicks, "air," etc. are not themselves

Now let us see how these processes are characterized according to 1a-g, and 2a-d from section 2.1. For the sake of brevity, we will primarily discuss the convection currents and heat flux/flow.

(1) Processual features:

  (a) Generality: Convection currents and heat flow have no location, in that they extend indefinitely through and beyond a system of study, both spatially and temporally. However, we can localize each by imposing epistemic constraints of degree-of-relevance to the system under study and the operations we perform on the system (both as interventions and the sensitivity of our measurement apparatuses). These operations allow epistemic and pragmatic isolations of the convection currents and heat flows that are relevant and those that are not. E.g., the relevant convection currents are those that have measurable significance to the cooling of the cup of the

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described by collections of more-stable processes. This response is presented thoroughly in Penn (2023, Ch 2), and applied to the specific case of the candle flame in Penn (2023, Ch 3). Second, and more relevant for the present discussion, even if we accept the premise of this objection, we must still admit that the candle flame is characterized and identified by the motions of these substrate underliers. No feature of molecules or atoms alone could be sufficient for a description of the candle flame, without metaphysical extravagances like ill-defined and dubiously knowable potentials, causal powers, or dispositions. The processes of the candle flame are therefore essential to any realist description of the candle flame system.

candle. This measurable significance decreases systematically as we measure the cooling effect farther from the combustion zone through interventions on the system to isolate it from less and less environmental air flows. Thus, while the convection current is not a local particular thing, we can consider its local impact through epistemic means of localizing its measurable impact.

(b) Subjectless: This is perhaps the least obvious. Convection currents do not occur in a subject, nor are they changes in a subject. They are change, a flux, a flow, measured through experiments and observations that allow us to measure, for instance, the dynamic response of a buoyant body to these convection currents (e.g., a feather over the candle flame). A common argument—called an underlier argument in Penn (2023, Ch 2)—goes that convection currents occur in air, and/or are the changes in the moving particles of air. These arguments fail for a systematic reason: they cannot rule out that the proposed underlier is not itself a process. However, in this case, convection currents cannot have the measurable features they do if they are mere adverbial predicates of an underlying subject. This is because the flux of heat and oxygen that are used to identify convection currents are never measured with respect to any single collection of particles, nor any indefinite collection of any particular size, nor any single subjective substance like "air," nor even in terms of individual motions taken in aggregate. This means that the subject of "convection current flow" is at best an indefinite something, like "air" or "this region of the system here." But if the subject is itself indefinite, we should be skeptical that it itself is not better understood as a process rather than a definite object or thing. Moreover, the linguistic point, that descriptions of convection currents require noun-like subjects (which would be a linguistic-metaphysical reason to suppose that there is a noun-like referent for such speech acts) is dubious. Throughout this discussion, I need nothing more than the phrase "convection currents" to talk about this process, making reference to underlying systems only in those instances where I provide a means of measuring interesting features of these process.

(c) Occurrent: This is trivial. Convection currents, heat flux, capillary action, radiation, combustion, etc., are all non-momentary, and non-static. They are therefore temporally extended, occurring over a duration, no matter how small.[7]

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[7] It may be interesting for the reader to note that there may be a smallest duration that is physically measurable. At such a limit, the proponent of more substance-paradigmatic forms of realism may be able to argue that there are necessary entities in the world that are in principle unmeasurable, but must exist to ground the

(d) Measurable: One cannot count convection currents, or heat fluxes, as one might think to count chairs. Instead, we provide a means of identifying features of convection currents through measurement activities. These measurements in turn allow us to talk about the manner in which convection currents interact with other processes, and to compare them systematically. For instance, in the candle flame, we identify the convection currents with three relevant measurables: heat flux, oxygen flux, and incandescent-combustion-product flux. Each of these measurables are measured by specific activities of the experimenter. Oxygen flux—which is relevant to quantitative descriptions of how necessary interactants in the chemical reaction of combustion are delivered to the relevant interaction zones—is measured by perturbation of ratios between the oxygen flow in the external system and flows of other combustion components (paraffin, heat). Decreasing the oxygen flow in the external environment proportionally decreases measurable features of, e.g., combustion (its rate, its purity, etc.).[8] By

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measurement of the processes at that energy-time scale. I invite readers with the intuition that such entities exist to produce them, since this would constitute a strong argument against a purely processual ontology.

[8] It may be worth noting that measurable systems are not generally countable. First, any measurable variable that takes continuous

concatenating these measurements, we construct a systematic account of how and to what degree convection currents function on the candle flame to produce, e.g., its shape, its persistence, its specific heat flow, its incandescence, etc.

(e) Determinable: Convection currents have no intrinsic character that would allow them to be defined independent of a means

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values will be mathematically uncountable. Second, we can imagine many physical systems that are measurable where countability does not follow. Measurables such as momentum, energy, energy flux, dispersion, angular diffraction, duration, displacement, length, probability, and so on take values of measurement but are not themselves countables. It would be wrong to say that "there are three energies here, or six momenta." Such statements acquire meaning only when we understand these measurables as instantiated in a countable object. So, for instance, there can be three measurable energies only when there are three identifiable and independent systems that possess this measurable. Qualitative examples (rather than quantitative) are similarly illuminating: how can one count the number of snowfalls, or the number of currents in a river? This is the point: processes (like movement, flow, growth, decay, etc.) have measurables (like momentum, flux, dispersion, etc.) that allow us to quantitatively compare them to each other (this current is stronger than that, this motion is faster than that, this motion is harder to inhibit than that, etc.), but processes are never countable. This is quite distinct from things, or objects, or structures. I can count the number of triangles in many systems, and I can count the number of objects in a system, even if those objects themselves have measurables that do not admit of countability (such as the momentum of an electron—the momentum is never countable, even if we suppose (dubiously in many systems) that the electrons that bear momentum are countable).

of measuring, identifying, recognizing, and/or observing them (not necessarily by humans). In a wash of air flow, what makes a sub-process of this flow a convection current is all of the means by which I, or another system, could interact with the larger air flow to functionally differentiate one stage of that flow from another, the convection currents specifically. To be precise, convection currents are determinably identified by characteristic energy and heat gradients that match or mirror energy and heat gradients in fire, flame, or radiating bodies. This makes them determinably distinct from air flow in general, the heat-energy-pressure gradients of which are not necessarily mirrors of combustion or radiation sources.

(f) Contextual: Convection currents cannot be understood in vacuo (pun intended). They can only exist insofar as there is an episystem that can, for example, admit their characteristic heat and kinetic flux as influx and outflux. Similarly, their generality (localizability) requires us to suppose that they are characterized in part by reference to this episystem in which they participate. E.g., the act of localizing a process requires us to simultaneously negate that the process is relevantly active in the dual of the region in which we localize it. Contrast this with things, objects, structures, substances. These entities (supposedly) have features that are definable, knowable, or constitutive independent of any other system. A thing-description of a table, for instance, requires no commitment to the existence and specific features of what lies outside of the table. The table just has a shape, a mass, parts, functions, etc. This is not true of processes like convection currents.

(g) Pragmatic Divisions: Convection currents can be discussed in terms of stages, even though they are not mereologically partitioned into such stages. For instance, by reference to the localization and measurement activities described above, we can talk of the convection currents before and after combustion, or below and above the combustion zone. These stages (before and after, below and above) are often pragmatically useful when we model the system, but they are represented in our models by reference to specific functional differences in the whole convection current process. E.g., one stage is said to deliver oxygen to, the other to carry it away from, the combustion zone.

In this account of convection currents, we have a specific entity being posited by the process realist. Namely, the convection current is a real process, characterized by a specific list of measurables and means by which these measurables could be given values, identified with respect to an experimental episystem, and bearing meaningful dynamic relations to other processes that interact with the convection current's measurable features. These processes also enter into conceptual relations with each other that allow us to differentiate and compare processes described in a model. E.g., convection currents are types of heat flux, but they are not the heat flux of combustion, or radiation. Instead, they interact with these other real processes to measurable degrees.

[2.3]: The Core Supporting Argument

Pure process realism unifies and supports a plethora of process-adjacent interpretations of scientific models.[9] Process realism does this by offering a single argument to generally defend these positions: the continuity argument. At its most simple, the continuity argument goes that the essential components of scientific epistemology—experiment, observation, and systems-intervention—are physically (and psychically) impossible without the existence of dynamics. We imagine "a room in which nothing changes… what can we observe in, experiment on, or infer about this room? The simple answer is: absolutely nothing." (Penn, 2023, p. 12). Processes, then, are ineliminable from our empirical practice. A minimal account of scientific epistemology requires commitment to real processes.

From this, we can construct interpretations of scientific models as identifying novel processes that are continuous

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[9] See Barwich (2018), Chen (2018), Dupré (2014, 2018), Earley (2008a, b, c, 2012, 2016), Ferner and Pradeu (2017), Finkelstein (1996, 2008), Guay and Pradeu (2015), Hartman (2005), Jungerman (2008), Kaiser (2018), Malin (2008), Meincke (2018, 2019), Pemberton (2018), Pradeu (2018), Riffert (2008), Stapp (2008), Tanaka (2008). More recently, Longino (2020), Bokulich and Parker (2021), have all made moves toward process interpretations of science, with the caveat that they do not explicitly commit to some version of process ontology.

with, and contextually identified by, the processes of our interventions, observations, and experiments.[10] In short, we may commit to any process that our models identify via reference to these experiments. For example, we may call a phase transition a real process since it appears in our models as continuous with the intervention process of applying heat to a system, and with observed signal processes like the altered reflection of light from the newly transitioned system.

Importantly, the continuity argument is not a typical indispensability argument. Traditional indispensability arguments are formed by suggesting that there is something about the descriptive aspects of scientific models and theories that require us to commit to something metaphysical. For instance, one can read certain structural realists as offering just such an indispensability argument for the mathematical structures of many advanced physical theories. The fact that the relevant theories and models seem to necessarily be quantitative, containing as essential components mathematical relations in the form of various equations, functions, or functionals, suggests that these mathematical relations are descriptively indispensable, and so must be reified (i.e., promoted to the metaphysical, not epistemic or pragmatic, status of "real").

Process realism offers an argument in a similar sense. However, there is a key difference. The continuity argument presented in Penn (2023) asks us not to look to the descriptive practice of scientific modeling, but the practical, and physical, application of our models in the world. I.e., rather than seeking some inferential connection between semantics or syntax and the metaphysics of science, process realism asks us to notice a connection between the

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[10] N.B. Process realism also allows that some processes can be identified by reference to the contextual processes of the more social aspects of scientific practice as well. See Longino (2020).

epistemology of science as a manifest practice and the metaphysics of science. It is physically impossible, so the argument goes, to perform an experiment, to observe a star, or even to discuss and build theoretical and abstract models in the absence of physically real processes. The continuity argument then allows us to take this general idea and generate precise commitments to the processes described in scientific models (Penn 2023, Ch. 1).

The difference between these two types of indispensability can be made apparent by noting how each might be refuted. The Semantic Indispensability argument is refuted by noting the possibility of redescription. If it is possible to reformulate a scientific model semantically without breaking its applicability, explanatory content, etc., then the semantic indispensability argument falls flat.

In contrast, the physical indispensability of the continuity argument could be refuted only by providing a physical, or metaphysical, means by which the epistemology of science could occur in a manifest physical world that does not require the existence of process and change. We might imagine such counter-exemplars—worlds filled with beings that know a priori non-trivially, and formulate their models of the world with godlike instantaneity and eternality in platonic heaven—but these counterexamples will appear in worlds that are wholly distinct from the one in which we live. In our world, scientific models, experiments, and theories are themselves occurrent, not continuant.

This is the strength of the continuity argument, a strength notable even in the discussions of empiricists and scientists. While both might deny that their models semantically represent the world as it is, neither camp will find it plausible to deny that their activities as scientific knowers cannot exist in an unchanging world. I.e., processes are a minimal presupposition of the physical possibility of scientific practice, empirical and theoretical.

[2.4]: Satisfying the Realist

The process realist constructs fecund interpretations of scientific models, not merely bare descriptions of experimental/observational activities. This means that process realism satisfies what Chakravarty (2007, Ch.1) describes as the "metaphysical dimension of realist commitment."[11] In simple terms, process realism does indeed count as commitment to entities—processes—that are, in some sense, "external" to the observer.

However, process realism commits us to this "external" reality without admitting that these systems are ever definitionally *independent* from our observational activities. The processes to which we commit in our models are just those that are participants in our experiments, broadly understood. These participants are dynamically continuous with "direct observation" activities. This means that the real entities of process realism are not mind-independent in the most strict sense, even though they are not called strictly mind-dependent either.

Nevertheless, the realist's metaphysical commitment does not require us to believe in strong independence. Firstly, several realist positions would be unreasonably excluded from the canon if we were to enforce this

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[11] See Psillos (2007, 2017) for a different characterization of the realist debate. Psillos's characterization focuses primarily on the nature of theoretical claims, and is therefore put in terms of two semantic dimensions (truth and reference) and a historical dimension (continuity with past models). I contend, but do not directly defend, that this characterization can be satisfied by the process realist as well, with caveats.

requirement.[12] Secondly, and more importantly, to require independence in our metaphysics is to explicitly reject a metaphysics in which the ontological primitive cannot exhibit independence as a categorical feature. So, to require mind-independence is to call process *metaphysics* illegitimate as a metaphysical position, since process metaphysics is committed to (1f) above. This would be an untenable position to defend, and so the realist should not be troubled by this aspect of process realism.

Process realism similarly satisfies the other dimensions of realist commitment, again with caveats. The realist is also said to be committed to the semantic truth of scientific models (Chakravarty 2007, Ch.1; Psillos 2007, 2017). Typically this is understood as commitment to the literal truth of model claims or terms. That is, scientific claims have truth values, and typically, these truth values are offered by some truth maker in the world. "…to have a good reason for holding a theory is *ipso facto* to have good reasons for holding that the entities postulated by the theory exist." (Wilfred Sellars, 1963, p. 97).[13]

The process realist significantly alters this commitment. Process realism is committed to the idea that scientific models truly describe the world. However, process realism cannot rely on orthodox accounts of truth. After all, such orthodox accounts are entangled with the substance paradigm, the metaphysical antithesis of the process paradigm (Seibt 1990, 1996a-c; Penn 2023, Ch.2). Specifically, orthodox accounts of reference require the referent to be definite, determinate, and often nameable (countable). Processes lack these features (by 1d and 1e

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[12] See Massimi (2022) for perspectival realism, and Chang (2022) for pragmatic realism. Both would not count as forms of realism if we demanded strong mind-independence for our realism.

[13] See also Sellars (1952, 1981) for his processist turn.

above). However, this is simple to resolve. Process realism provides processual referents in our scientific theories by identification activities, such as measurement and intervention. I.e., reference in process realism is an activity of the referrer, not a relation of a term to a referent. See Seibt (2010, 2015), for general approaches to processual reference and Penn (2023, Ch.2, 5) for extensions to scientific domains.[14]

The process realist also holds that scientific models and their claims constitute knowledge of the world. This is an easy commitment to meet: the entities to which we are committed are just those that are identifiable through good epistemic methods, namely, scientific practice. As such, so long as we take science to be an epistemic method, process realism will satisfy the epistemic requirement of the realist.

Last, the process realist should be loath to couch any interpretation of science in definite terms. As such, they will largely remain quietus (or in opposition to) the distinction between epistemic achievement vs. epistemic aims (c.f. Van Fraassen 1980, p. 8). There is no end goal or final state of science for the process realist. Rather, both the aims and achievements of science are auxiliary parts of a dynamic, ongoing process of evolving methods, data collection and processing, model construction and application, theory building and confirmation, and so on. Science is epistemic for the process realist because its practice involves these dynamic evolutions, not because it aims at or achieves definite truth.[15]

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[14] See also Suárez (2003), who offers a discussion of scientific reference that is highly amenable to the process realist, if not explicitly aligned with the view.

[15] See Kitcher (1993) and Psillos (1996; 1999) for general presentations of the continuity of scientific advancement, and some upshots. See also Bain and Norton (2001), and Bokulich and

These points are perhaps best illuminated by showing how process realism differs from instrumentalism and empiricism. The difference is simple to express: process realism commits to real, knowable, semantically potent entities in an external world, specifically, processes like convection currents, river erosions, spectral radiations, snowfalls, RNA transcriptions, species phylogenetic developments, and more. Unlike the instrumentalist, the process realist is not merely advancing the claim that scientific models are about the functional inputs and outputs of experiments. Rather, the process realist uses the activities of experimenters and observers that are represented by these functional relations to determine, identify, characterize, and then commit to real entities like convection currents as they are described by the relevant models. This is just to say that process realism is a full-throated empiricist epistemology coupled with a fecund naturalist metaphysics. It just so happens that this metaphysics is highly integrated with and dependent on empiricist epistemology (as I argue below).

However, more nuance is warranted in this response. Process realism constitutes a commitment to a real metaphysics as described by scientific models, but it requires us to fundamentally change many of the presuppositions that have been left under-examined in the history of realism. Perhaps most salient among these is the presupposition that a model describing the world is constituted by some absolute relation between the language of the model and the referents in the world. This presupposition precludes that a model could describe a world of processes, since processes are not definite/determinate. If we must take descriptions of the

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Parker (2021) for more specific discussions of aspects of this. See Penn (2023, Ch. 3, 4) for an extended example of how process realist interpretations survive several centuries of theory change. This is an important point that is discussed more in later sections.

world to always refer to definite entities, then processes are simply beyond the scope of what a model could describe. If we suppose further that we cannot obtain a realist account of our models without taking the models to definitely describe the world, then process realism becomes incoherent.

But this is not the case, as demonstrated above and elsewhere. This argument, that process realism is incoherent, conflates literal description of the world with definite description of the world. A literal truth is just one that is sufficiently restricted by or based on fact, i.e., whatever is knowably the case. A definite truth is literal, surely, but it also comes loaded with additional metaphysical baggage, specifically, the further constraint that facts are of determinate things, or are themselves determinate things.

Process realism requires us to un-equivocate the literal and the definite. Processes can be literally described by models—I have sketched, and will discuss below, how this description is enacted by reference to specific and actionable activities of measurement, intervention, observation, and so on—even if processes can never be definitely described by models. This literal description looks like a proscription of activities we might use to identify processes in the world. As such, it looks quite similar to various forms of empiricism, including those with instrumentalist, verificationist, or operationalist flavors. However, process realism remains a commitment to more than merely the epistemic-pragmatic position of the empiricist. Processes are real.

[2.5]: Notable Departures from Other Realisms

The preceding demonstrates two points. First, process realism is indeed a form of realism. This would likely be uncontentious, were it not for the second point. That is, process realism does not rely on—and indeed eschews completely—many of the arguments for realist positions found in the history of the debate. Corollary to this, process realism comes with significant constraints, as discussed below.

Most notably, process realism remains free of the no-miracles argument, and its variants. The continuity argument does not trade on the likelihood of successful science in the absence of real processes, nor on the corroboration of processes amongst many models, nor even on the usefulness of positing processes in order to explain. Instead, process realism is built on the recognition of the physical and psychical nature of empirical practice. It may turn out that there is some possible world in which experiments and observations can be performed in the absence of physical and psychical processes, and even a dualist world to make sense of this distinction. However, *that* world is not *this* world. In our world, processes are necessary, because experiments and observations are processes, as are the intellectual acts of modeling systems.

This is a significant departure from orthodox realism. Arguments for orthodox realism are many in form, and so varied that it would be impossible to represent them all here. However, they share one key similarity: every argument for orthodox realism rests on the inference to an underlier for the processes of scientific practice. This involves two logically separable inferences. First, that experiments and observations are actual goings on, and our models are descriptions thereof. Second, that what conceptually allows for these descriptions is the existence of some definite, particular, non-contextual entity, a continuant to underlie change. This entity may be a structure, a thing, an essential nature, a substance, a classical particle, or any other of a number of substance-paradigmatic entities. Since this underlying entity is thing-like, it cannot respond to experimental dynamics, nor can it produce signal dynamics. To do so would be to become process-like. This underlier is therefore in-principle independent of the acts of observing the system for which it is an underlier (Penn 2023, Ch.2). And it is precisely this inference to this underlier that the antirealist finds (rightly!) troubling.[16]

This means that we can already anticipate the manner in which the process realist will assuage the worries of the antirealist. By denying the need for any more thing-like entities—definites, particulars, non-contextuals, etc.—the process realist also does not need to infer the existence of anything that is not already participant in the activities involved in the practice of science.

[3]: The Antirealist's Worries: Hidden Things

The antirealist's criticisms are many and varied. This section is not meant to offer comprehensive accounts of the various concerns. However, I argue here that most of the criticisms offered by the antirealist stem from two more general worries:

(1) A worry about the history of science, its role, and its prescription for the future.
(2) A worry about overextending from empiricism, i.e., a rejection of a priori reasoning, and rationalist epistemological methods in general.

Both of these amount to the following: that the realist's interpretation of science is too static to handle the dynamic

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[16] See Penn (2023, Ch 2) for a full analysis of all underlier arguments, both in the realism literature and in domains outside of philosophy of science.

nature of scientific history and practice. Both (1) and (2) reflect this worry, as I show in this section.

[3.1]: The Pessimistic Meta Induction

The most storied objection to realism,[17] the pessimistic meta-induction (PMI) finds its contemporary locus in Laudan (1981). Laudan argues that the history of science contains many examples of scientific models that are explanatory, empirically successful, and/or seemingly accurate or true, but which later turn out to contain posits that are false. Famous examples include the phlogiston theory of heat, and luminiferous aether, and vital essences, all posits that informed successful theories of their time, but which were ultimately disproved. From such cases, we induce that no scientific model is wholly without failures of reference, explanatory success, or empirical support. Thus, whatever aspects of our models we wish to interpret along realist lines may, in fact, be a false posit.

The PMI is a concern that stems from the intuition of the seeming discontinuity of the history of science. Psillos (2017) shows that this intuition is far reaching, and has its roots in many similar concerns. Hesse, for instance, presents a "principle of no privilege," which states that "our own scientific theories are held to be as much subject to radical conceptual change as past theories seem to be." Hesse uses this principle to suggest that "Every scientific system implies a conceptual classification of the world into an ontology of fundamental entities and properties… But it is exactly these ontologies that are most subject to radical change. … It

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[17] See Wray (2015) for a survey of the formulations of this argument.

seems that we must say either that all these ontologies are true… or … they are all false." (1976, p. 266).

Similarly, the PMI is often expressed in conjunction with discussion of theory change along Kuhnian (1962), or even Poincaréan (1905) lines. We notice that scientific history seems to involve the development and subsequent rejection of scientific paradigms. Each paradigm specifically includes a lexicon of supposedly referential terms. Paradigm shifts therefore represent rejection of these lexica, meaning that the history of science is filled with the failure of realist claims of literal reference.

This means that the PMI is an epistemological version of the problem of change. The problem of change concerns the inability of substance-paradigmatic frameworks to adequately describe, explain, and otherwise capture the nature of change in the world.[18] Similarly, the antirealist worries that the realist, in seeking to acquire definite reference from scientific lexica that are demonstrably indefinite and evolving, represents scientific practice ahistorically. Kuhn describes this intuition in detail in a series of lectures:

> For much of the last decade I have been reexploring [the idea of theory change and the history of science], increasingly guided by the conviction that scientific knowledge can be properly understood only as a product of history, of a temporally and spatially continuous developmental process. These lectures focus on one product of that exploration: a set of problems concerning the nature and

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[18] See, for instance, Raven (2011).

> consequences of conceptual change. (Mladenovic 2022, p. 28).

The PMI, therefore, is an issue for any form of realism which seeks to fix the reference of scientific models independent of this "temporally and spatially continuous developmental process." If our realism is *too definite* or *too static*, then we will fail to account for conceptual and theoretical change, and fall victim to Hesse's principle of no privilege.

[3.2]: Underdetermination, Multiplicity, Perspective

Scientific history contains many instances where multiple models are used to describe similar phenomena. Sometimes, these are competing models describing the same system (Morrison 2011), sometimes competing models that are empirically equivalent or equally supported by contemporaneous data (Duhem 1906), sometimes the same model used for multiple competing purposes (Bokulich and Parker 2021).[19] Regardless, the complex pathways whereby the scientific community chooses amongst these competing models or interpretations is not the result of direct evidentiary support. Rather, the choice includes many contextual factors such as corroboration with other models and application of non-epistemic values.

These problems have many names: underdetermination, multiplicity, incompatibility, contextuality, etc. However, all pose the same issue for the realist: our reasons for treating any part of our models as real do not seem to stem exclusively from empirical data. Thus, the worry arises that

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[19] See also Longino (1990, 2002) for many examples of the multiplicity of models.

any realist commitment will be susceptible to the problems faced by non-empiricist epistemologies, since these commitments will stem from non-empirical support (support from values, contexts of use, perspectives, conventions, etc.).

The key, however, is to note that this complex of problems forces the realist to admit that their realist posits do not bear fixed relations to evidence and data. If we think that our model descriptions should be definitely, literally true, then we should think our data is similarly determinate. Underdetermination, and multiplicity considerations in general, confabulate this assumption, telling a story wherein data and our models are indefinite and contextualized to the ever-evolving circumstances of history and best practice. The problem, therefore, lies in the non-contextuality and determinateness of the realist's posits.

[3.3]: Abstraction, Idealization, and Falsity

We find many many cases where scientific models are not only strictly false, but essentially so. That is, we often idealize and abstract in our models extensively, in virtue of which our models are explanatory (Bokulich 2009, 2011, 2016; Cartwright 2010; Potochnik 2020), exploratory (Shech and Gelfert forthcoming, McCoy and Massimi 2017, Morrison 1999, 2011), and empirically supported (Potochnik 2020, Bokulich and Parker 2021). Moreover, idealizations and other fictional elements enable models to be contextualized to their pragmatic goals and the communities by which they are used (all above, Liu 2004). Idealizations, and other fictional elements, appear as key components in our models.

The difficulty for the realist is twofold:

(1) How can any model be said to represent the world as it is (through its explanations, explorations, reference, representation, or confirmation by empirical support) if we know that models are often successful in virtue of features we know are false/fictional?

(2) How can we choose a single scheme for realistically interpreting a given model when we know it contains features that make it successful only relative to its context of use?

Both of these are problems for any realism that seeks to provide determinate, non-contextual entities as referents for our models. The entities reified by orthodox realism are meant to be independent of the means of representing them, measuring them, exploring them, or otherwise interacting with them. Our empirical practice does not allow for the reification of entities that are independent of that practice. Such reifications chase unicorns.

[3.4]: Worries of Epistemic Warrant and Impact: Does Realism Affect Explanation?

Finally, an antirealist might worry that realism does not add anything to our interpretation of science; the metaphysics of science should be epistemically potent. We see this in Laudan and Ross (2009), and forthcoming work on quietism. The intuition is that we should approach scientific models with the aim of minimally interpreting them. Supposing that we can understand our models—their explanations, their successes, their exploratory functions, and their ability to target a system of interest—without a metaphysical commitment, that commitment should be discarded. If this can be extended, such that a metaphysical framework provides no epistemic benefits, then the whole metaphysical framework should be discarded. The worry is that metaphysics in general does not provide epistemic benefit, either as an entailment from or a constraint on scientific practice; science can be interpreted purely in terms of epistemic functions.

I do not think this worry is especially troubling to the realist. The criticism arises from a particular sort of historicizing of science, similar to the PMI. However, enough cases exist in history where metaphysical debates have constrained or been resolved by empirical practice. For instance, Boyle's chemistry came from and helped resolve a metaphysical debate between three types of alchemy.[20] Only one of these alchemical metaphysics—the atomist account—allowed room for the development of experimental methods for producing substantial (alchemical) change. Boyle made use of this metaphysical picture to develop his chemistry, with never a care that the atomist metaphysics would not be considered empirically supported until the work of Brown, Einstein, and Perrin.

Nevertheless, the antirealist is right to worry in one respect: wheresoever metaphysics fails to support or integrate with the development or practice of empiricism, it should be rejected. The realist's ultimate metaphysical framework must at least avoid anti-empiricism, and should strive to be fully integrated and essential to the practice of science. As Laudan and Ross (2009) express, scientific epistemology requires us to relinquish a metaphysics of self-

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[20] See, for instance, Levere (2001, Ch1, 2) and Lindberg (2008, Ch. 12). In addition, see the debate between Potter (2001), and Sargent (2004) for a discussion of interesting additional considerations in Boyle's work related to his understanding of metaphysics.

subsistent objects.[21] Others argue that scientific explanation is pragmatic and contextual, such that explanation does not make reference to underlying metaphysical truth.[22] The thing-like-ness of one's metaphysics is the problem, and remains a legitimate and persistent worry for the realist.

[4]: Resolution, or, Why the Process Realist Rejoices in Empiricism.

A common theme emerges from the previous section. Namely, the problems of antirealism all relate to problems with specific aspects of the ontology of the realist. The antirealist is (and should be) concerned by the non-contextuality of the entities posited by the realist because of the historical contingency and perspective-informed nature of models, as well as the need for contextual explanations for some phenomena. They are concerned by the determinateness of the realist's posits because of underdetermination, the multiplicity of incompatible models, and idealization. They are concerned by bottom-up

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[21] Laudan and Ross use this to argue for ontic structural realism, neglecting that structural realism must still admit of an ontology of determinate entities. Even if they are not objects, structures are still things, with thing-like features (determinateness, non-contextuality, countability, particularity (in some cases), etc.). Arguing this in detail would be rather difficult, since structures as an ontic category are left largely unexplained in the structural realist literature. One of the best accounts is found in Wallace (2021), but note that Wallace's structures are still thing-like, even if they are not objects.

[22] See, in general, authors such as Scriven (1962), van Fraassen (1980), and Woodward (2003).

metaphysics because of the dearth of examples of its explanatory impact.

Far from problematizing realism in general, the concerns of the antirealist inductively support a rejection of the categorical features of the substance paradigm. This rejection is systematic, and historical. The solution, then, is quite simple: adopt realism divorced from the substance paradigm.

The process realist assuages the concerns of the antirealist by systematically building their ontology from and within empirical practice. The nature of process ontology—the features described in section 2.1—makes it improbable for the process realist to commit the same mistakes as the orthodox realist. The process realist does not interpret scientific models as representing through definite, determinate, non-contextual reference. As such, the entities to which the process realist commits are not the sort to be subject to worries about change of either our models or our concepts, locally or broadly.

This in itself recommends process realism over its competitors; the resolution of the perennial debate between realists and antirealists is a significant achievement. However, the manner in which process realism resolves each specific antirealist concern results in many corollary constraints on process realism. Going through these specifics is the focus of this section. Our discussion will be aided by considering a particularly contentious example from the history of science, and generalizing from there.

[4.1]: The Bohr Model of the Atom

The Bohr model is an excellent test case for realism. First, the model is both a part of a trajectory of research in early quantum theory and a model used to this day (Blum and Jähnert 2022, Gao 2021). Second, it has clear empirical support and clear exploratory and explanatory use, suggesting it as a candidate for realist interpretation. Finally, the model contains elements that are strictly false, making a realist interpretation seemingly impossible. As I argue here, the model demands that we eschew classical substance ontological talk entirely, in favor of purely process talk. Doing so is precisely what allows a realist interpretation, and a better account of how the model fits into the history of science.

[4.1.1]: The Model

In 1910, following Planck's work on Black Body Radiation, and Einstein's light quantum paper, the physics community began to focus on atomic and molecular spectroscopy as the next target for quantization. Simultaneously, the discovery of the electron raised interest in developing an account of the atom in terms of electrons bound by a positively charged central mass. It was in this context that Bohr developed his planetary model of the atom (Bohr 1913a, b, see also Pais 1986 for a thorough historical analysis of this context, as well as the model itself). The model had the explicit intent of explaining why light absorbed and emitted from atoms did not come in continuous spectra; only light of very particular frequencies, measured by a spectroscope, was absorbed or emitted (atomic line spectra).[23]

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[23] Heilbron and Kuhn (1969) describe the origins of the Bohr model, as do Jammer (1966) and Darrigol (1992a). In addition, see Assmus (1990, 1992a,b) for an argument that the interest in spectroscopy was not solely due to Bohr's model, but also

The model is quite simple. Bohr posited that electrons in an atom exist in a discrete array of stationary energy states with definite energies. This array was defined by Bohr by the imposition of the quantum condition:

$$(Eq1): E_{Kinetic} = \frac{n}{2}hf, \;\; n = 1, 2, 3, \ldots$$

Where h is Planck's constant, and f is the frequency of revolution of the electron.Understanding that these orbits are circular—that the angular momentum M of the electron is given by the equation $M = 2\pi f a^2 m$ with a the radius of orbit and m the mass of the electron—makes (Eq1) equivalent to the more traditional expression of this quantum condition, namely that the orbital angular momentum M bears the relation: $M = n\frac{h}{2\pi}$. Transitions between these states are excitations or decays with energy equal to the difference between the energies of the two states:

$$\text{(Eq2):} \;\; E_{transition} = E_{initial} - E_{final}$$

Adopting the energy-frequency relation—that is: *E* = *hv*, where h is the Planck constant and *E* and *v* are the energy and frequency of light—Bohr then used (Eq2) to suggest that the energies of absorbed and emitted light were the result of light triggering or being emitted from transitions processes in the atom. The frequencies of light absorbed by and emitted from the atom would be derived in the following manner:

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appeared in the community of physicists working on specific heats in thermodynamics.

(Eq3): $E_{transition} = E_{light} = h\nu$

(Eq4): $\nu = \frac{1}{h}(E_{initial} - E_{final})$

Given the discrete energy states that defined the initial and final energies, indexed by the number $n_i = 1, 2, 3,\ldots$, this meant that the series of frequencies that could be emitted or absorbed would be defined by all possible transitions between $n = 1, 2, 3, \ldots$ energy states.

Conceiving of these energy states as orbits for electrons allows for the following model description of the phenomenon of atomic line spectra. A photon of frequency ν strikes an atom's orbiting electron. If this frequency corresponds to the energy difference between two orbitals, the orbiting electron acquires the energy of this photon $E = h\nu$ and jumps to a new orbital with higher energy, absorbing the photon. Then, since the electron is in an excited state, it is unstable, and so will eventually decay, falling back to its lowest-energy orbital along some path through the intervening orbitals. With each decay transition, the electron releases a photon of frequency $\nu = (E_{initial} - E_{final})/h$.

This model works exceptionally well for hydrogen atoms and their line spectra (given by the Balmer Series). However, Bohr recognized a key problem: orbiting electrons will emit energy continuously as they orbit (Bohr 1913a, 1).[24] This is

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[24] See also Pais (1986, 209) for an account of how Lorentz raised the objection of the mechanical explanation and possibility of fixed orbits. Bohr, reportedly, responded that this was a significant and lingering objection, but that "some sort of scheme of the kind suggested was necessary." Bohr also considered a similar objection raised by Rutherford in a letter written March 20, 1913, just before publication of Bohr's paper: "There appears to me one grave difficulty in your hypothesis which I have no doubt you fully

because orbiting electrons are accelerating radially inward, and accelerating charges emit electromagnetic energy. This means the "stationary" orbits, classically, would not remain so for long Bohr's key move, then, was to demand that these orbits are stationary (Bohr, 1913a, 7). However, such a demand raised further problems for the Bohr model, namely that there was seemingly no mechanical or causal explanation for why these orbits were stationary, or why an electron would reside in or jump to them specifically (Bohr 1913a, 7; see also Rutherford 1913). So, the orbits as described are either physically impossible or else merely placeholders for future mechanical descriptions, as Bohr himself acknowledged. Either way, the stationary orbits cannot be interpreted literally.

It should be noted as well that this was not the only historical objection to Bohr's model. Pais (1986) also describes several other responses, including the initial objection that attempts to extend the model to Helium ions produced conflicts with experimental results for the Rydberg constant. This led Bohr to quickly modify his account by adding additional terms representing the ratio between the mass of the electron and the mass of the nucleus, which restored the applicability of the model to He+. However, further considerations of how the Bohr model might be applied to Helium ions led to several greater problems. First, Bohr's model seemed to imply that all transitions between states should be acceptable, resulting in 12 possible spectral lines for He+. While all twelve could be observed, it was only possible in the presence of an external magnetic field.

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realize, namely, how does an electron decide with what frequency it is going to vibrate and when it passes from one stationary state to another? It seems to me that you would have to assume that the electron knows beforehand where it is going to stop," (Rutherford 1913, Pais 1986, 212).

This led to the proposition of a quantum selection rule for He+, namely that changes in angular momentum quantum number are restricted to increments of plus or minus one. However this restricted the spectral lines from twelve to five, when experimentally six were observed. Further selection rules were then applied by Uhlenback and Goudsmit as late as 1925 to deal with this problem (Pais 1986, 214-215).

In general, the Bohr model was only successfully extended to He+ and then to neutral Helium after quantum mechanical methods and explanations could be incorporated into the model. This involved the resolution of Lorentz's, Rutherford's, and Einstein's worries about the specific mechanico-causal account of the orbits themselves. Specifically, considerations of spin, Pauli exclusion, and the development of both Schrödinger wave mechanics and Heisenberg matrix mechanics (which Pauli used to derive the Balmer series for Hydrogen), allowed for the model to be more generally applied. In especially the development of matrix and wave mechanical explanations, we see that, largely, what was missing from the Bohr model was a quantum mechanical explanation for the orbits (c.f. Pauli 1926, Schrödinger 1926).

[4.1.2]: The Process Interpretation

The natural question for the realist is: can this model be interpreted along realist lines at all? Those inclined to view the model in terms of its structural features, its object-like features, and more generally in terms of things will likely say that the model should be discarded in favor of the models that would be developed in the years following its initial conception. For instance, the representation of a circularly orbiting electron contained in the adoption of the equation $M = 2\pi f a^2 m$ is classically derived, and so is in tension with the demand that these "orbits" be non-classically stationary. This assumption of circularly orbiting electrons, then, is merely heuristic—rather than literally true—for developing the quantization of electron energy states without a further, quantum mechanical explanation. However, to treat the model as unreal would be to admit that a model that is successful in its explanations of a particular phenomenon (the Balmer series atomic line spectra) is unreal. Moreover, the model was used as an exploratory tool as well, to develop later models that eliminated and/or ameliorated the troubling aspects of the original (see Blum and Jähnert 2022, Pais 1986). Given that most arguments for realism find at least some warrant or motivation in the explanatory power of models, the Bohr model is a troubling case for the realist: it is precisely the sort of model that seemingly supports the PMI.

The process realist responds that we were never expected to commit to the Bohr orbits (nor indeed to orbiting electrons—c.f. Schrödinger 1926). Instead, the orbits are mere idealizations that enable the identification of the relevant and interesting dynamics for which the model was built. Specicially, we use these heuristics to identify the electromagnetic processes that fill the dynamical gap between the incidence of the radiation and the final emission of radiation that we observe through the spectroscope. This identification is done by contextualizing the system's dynamics—the electromagnetic transitions—to the intervention processes we would perform and signal processes we receive: the bombardment of the atom with light and the emission of spectral lines. These processes are real, and are characterized in detail by the Bohr model with measurable features like the energy of the transition, and eventually the changes in angular momentum and spin that were added in later, more nuanced models. (See Pauli (1926) for the representation of the dynamics of the hydrogen atom without reference to the Bohr orbits, following the matrix mechanical representation of Born, Heisenberg, and Jordan (1925)).

The process realist has a good, principled way of selecting the real parts of the Bohr model from the unreal parts. Namely, the unreal parts of the model look like non-dynamic aspects of the model: aspects that do not meet the categorical features of section 2.1. Namely:

(1) Aspects that represent static entities, or otherwise do not admit of dynamic interpretation
(2) Aspects that seemingly represent, but do not identify, dynamics (dynamics that are not identified by continuous, experimental dynamic contexts, following 2a-d in section 2.1).

The Bohr orbits are static states. Later models would refine the Bohr model by showing how these states are not static but *stable*, as standing waveforms of matter waves.[25] The

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[25] It is worth noting here that all accounts of stability are ultimately dependent on processual descriptions. A system cannot be called stable without identifying both a process under which the system is unperturbed *and* a process by which the system would be destabilized. Often, this is done implicitly by the context of discussion. For instance, if I remark that my table is stable, I mean that it will not be perturbed by my frenetic typing, while recognizing that there are other processes (like beating it with a hammer) that would destabilize it. For more on this, see Penn (2023, Ch 2, especially section 2.3). This recognition—that stability can be understood (and indeed can only be understood) process-ontologically—is what allows us to notice that many important physics concepts like stationary and equilibrium states will not be eliminated by process interpretations. Rather, such concepts will be given their proper due, as recognitions of how models often mark differences in the energy and time-scales of target processes in order to differentiate between relevant and

process realist contends that we can understand these non-dynamic parts of the model as idealizations. They are pragmatically useful, but without realist import. I.e., Bohr orbits (and all thing-like terms) are not essential to the explanatory and exploratory power of the model.

Let us see how this works. We start by noticing that the Bohr model represents a shift in the understanding of the origin of electrodynamics. In classical electrodynamics, the origin was supposed to be the result of accelerations of charges, i.e., the emission of energy from oscillating, underlying electrons. However, in the developing quantum paradigm, this is not the case. Electromagnetic energy is understood instead as the result of transitions without underliers (Blum and Jähnert 2022).

Bohr recognizes this in response to the criticism paraphrased above, that the stationary orbits of the electrons would collapse. He suggests instead that we adopt a purely instrumentalist understanding of the ground state (closest orbital) of the system. The ground state is not literally an electron orbiting the atom, but is rather the binding energy corresponding to that emitted by an electron brought close to the atomic nucleus from a great distance (1913, 5-6, 11-12).[26] In other words, we replace talk of orbitals in favor of instrumentalist descriptions of the bound energy state. Such talk is merely a placeholder for collections of experimental activities we would perform on the system in order to prepare it for observation, and thereby identify real

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irrelevant environmental or epistystemic dynamics. This is, essentially, the key point of Joseph Earley's (2008a-c) work.

[26] See Tanaka (2008) for a discussion of how Bohr's idea of complementarity is related to a shift toward processist interpretations.

processes.[27] We expect to eliminate such talk entirely with the development of better models.

In the Bohr model, this is simple. An electromagnetic process characterized by the measurable features E and v (related by $E = hv$),[28] interacts with our system to initiate another electromagnetic process characterized by measurable E and different contextual features to be determined in other models.[29] This second electromagnetic process is succeeded by a third sequence of processes, divisible into sequential processual stages each characterized by a measurable $|e_i| < |E|$, with total energy $-E$. This sequence of processes results in one or more electromagnetic processes similar to the first, each characterized by e_i and v_i related by $e_i = hv_i$, for each i.

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[27] Note this is a generally accepted feature of the shift in physics from classical to quantum. David Finkelstein expresses this as follows: """Classically, knowledge is a mental representation of things as they are. An ideal observation informs us about its object completely and without changing it. … [but] in a quantum epistemology, knowledge is a record or reenactment of actions upon the system" (1996, 18). In other words, we eschew talk of things entirely—including talk of orbits or electrons—in favor of talk of records of actions on and reactions of

A system.

[28] When relevant, we might improve the characterization of this process by adding additional related measurable features, such as polarity.

[29] This would be the place where, when we improve on the Bohr model, we would add in measurable features of the system like spin, angular momentum, spin-spin interaction energies and spin-momentum interactions energies, the dynamic response of the system to externally imposed fields, and so on, to further characterize the non-degenerate energetic features of the second energetic process, the transitions.

Nowhere in this must we mention that there are electrons, photons, or Bohr orbits. Instead, we provide measurable features of the system to characterize the salient details. This leaves us with a collection of processes identified with varying degrees of experimental precision through their measurable, dynamic contexts. These contexts give us license to search for more precise characterizations by the addition or precisification of relations between these measurables. Moreover, we notice two points: (a) we explore more precise characterizations without fear that we will contravene the original identified processes, since these identifications are related to experimental dynamics, not to literal referents, and (b) this exploration and precisification through addition of measurables and more nuanced experiments is exactly the trajectory by which the Bohr model developed in history (Blum and Jähnert 2022).

In addition to these local upshots, we see two generalizable points. First, this characterization of the model provides an explicit account of the exploratory functions of the model. We explore using a model by taking the original thing-talk and replacing it with newly identified or more nuanced dynamics. This enables our second point: the Bohr model and models in general are not fixed. Rather, they exist as processes themselves, participant in the evolving intellectual context of the community that employs them. They are dynamically continuous with past and future models, developing from the one into the latter. This is evident in the history of the Bohr model. The model was not rejected and discarded, but rather modified and improved. We therefore enact the process-interpretational shift without loss of explanatory power, nor loss of historical fidelity. Indeed, the process realist description matches better the history of science.[30]

[4.2]: Resolving Revolution

The discussion above enables the process realist to resolve the worries of the antirealist in detail. Importantly, this will result in both upshots and constraints on process realism. I proceed through each in fluid order here, and collect them in a list at the end of the section.

[4.2.1]: Idealizations are Thing-like

In the process interpretation of the Bohr model, we gave a very particular interpretation to the idealizations of the model. There are roughly three different types of idealization in the model:

> (1) *Idealizations of identifying origin/goal, or endpoint idealization*: Where we identify a process with a placeholder term for the endpoints of that process, idealizing away the necessary dynamic extension of our means of actual identification. E.g., the posit of orbitals, or energy states, that identify the beginning and ending of the transition processes by eliding the perturbative interventions that initiate these transitions, and the signals that are generated by them. These orbits are idealizations for the loci for perturbative, experimental intervention on the system.

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[30] See Penn (2023, Ch 3, 4, 5). See Early 2008a-d, 2012). See Gao (2021).

(2) *Idealizations of context*: where we assume that there are no contextual dynamics, or that we can isolate the system from these contextual dynamics. E.g., the assumption in the Bohr model that there is no additional perturbation of the system by external magnetic fields or internal spin-spin interactions.[31]

(3) *Idealizations of vehicle/underlier*: where we describe processes that are as-yet imprecise in certain expected aspects, or that relate to other modeled dynamics in unexplored or underexplored ways, by treating them as the actions of an underlying vehicle. E.g., talk of electrons and photons and nuclei as vehicles for the relevant electromagnetic transition and interaction processes identified by the Bohr model.

I do not suggest that we generalize these types of idealization; I tend to agree with arguments such as Liu's (2001), that there can never be a general account of the types of idealization. However, we can generalize *from* these three types in the Bohr model to a general recognition: idealizations are related to the temporary or heuristic rejection of one of the features of processes (1a-f, and 2a-d in section 2) to allow for determinate and simplifying descriptions of the system dynamics of interest. Further, idealizations are false because they necessarily represent non-dynamic entities.

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[31] Notice that we eventually eliminate these in order to simply produce more precise, more finely grained models of the dynamics of atomic line spectra. These idealizations might better be called abstractions, since they are not strictly speaking always false. In a singlet hydrogen atom, it is perfectly possible to isolate it enough to treat it as unperturbed and unaffected by additional internal interactions.

Both the endpoint idealizations and context idealizations in the Bohr model are idealizations about the contextual nature of the transition processes: they help us to treat external field interactions and small-but-interesting internal interactions as negligible to the identification of the transitions. The underlier/vehicle idealizations of the Bohr model instead allow us to ignore the deeper field-theoretic interactions whereby systems like electrons and photons can be described in dynamic terms.[32] Each idealization therefore elides dynamics by temporarily treating them as fixed.

This pattern applies to more complex examples of idealizations. For instance, the thermodynamic limit is a transition in model construction at which we effectively ignore the molecular and atomic dynamics of a thermal-statistical system. A thermal system is partially characterized by N, the number of interaction-carrying particles in the system, and V, the volume of the system. In the limit as both N and V are taken to infinity (holding their ration N/V fixed), statistical equations are transformed into macroscopic thermal equations. Often, this coincides with a shift in considering the system not as a collection of N particles, but as a continuous substance.

This poses a problem for orthodox thing-realisms: in the microscopic paradigm, we treat the vehicle of thermal dynamics as the atom or molecule (or other basic unit), whereas in the macroscopic paradigm, we treat the vehicle of thermal dynamics as a continuous substance. These are

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[32] It should be noted here that these field theoretic interactions would not be discovered until long after the Bohr model. However, the process realist does not need to know *what* deeper dynamics a given idealization hides, so long as they have a means of recognizing *that* something is an idealization within a given model.

incompatible ontologies, so long as we hold that these things are the subjects of our models.

However, when we adopt the process interpretation, we notice instead that macro- and microscopic thermal models are in fact just meant to describe and explain dynamics at different scales.[33] The lack of any decompositional and reductionist mereology in process ontology means that these different target dynamics need not bear any intrinsic logico-linguistic connection in order to *both* be real. And in *both*, the vehicle is a placeholder term, an idealization of thing-likeness that hides more nuanced dynamics for the sake of scope and explanatory success of the salient dynamics in the model.[34]

This provides the process realist with two heuristic characterizations of idealizations in a model:

(1) Idealizations of at-scale dynamics
(2) Idealizations of different-scale dynamics

At-scale idealizations include fixed descriptions of the endpoints and shape of processes, the points of intervention in a system. They conglomerate the contextual information necessary to identify a process of interest. This information includes all of the complex epistemological work done by practicing scientists in order to prepare a system for study: isolating it appropriately, determining targets and degrees of intervention, providing the system with appropriate output

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[33] See Batterman (2009) for a thorough description of the continuum limit in thermodynamics, and for an argument that supports the auxiliary (if not the primary) claims of the process realist, specifically that these different models are not reducible to each other and that they describe dynamics at different scales.

[34] See Penn (2023, Ch. 3, 4) for a more detailed and thorough investigation of historical thermal models.

receptors to properly read measurements of the target dynamics, the establishment of conventional language in order to discuss the system, etc.

Different-scale idealizations are idealizations about the vehicles of the system's dynamics. These are meant to represent the relative stability of certain aspects of a system with respect to the perturbations of our interventions and experimental manipulations. We may be interested in studying one set of dynamics at a given scale, and within a certain range of energies for the interventions we perform. At that scale, parts of the system will be stable throughout our experiments. We therefore treat these *unchanged* aspects of the system as if they are *unchanging*, thereby idealizing these aspects as thing-like.

However, we must always remember that stability is a relative term. The unchanged aspects of a system might always be perturbed by greater energies of intervention, or across greater time scales. For instance geological time-scale dynamics—shifting of plates, long-term climate patterns, etc.—are relatively stable in the context of daily fluid dynamics in a river or lake, and so we might describe the dynamics of these rivers in terms of unchanging banks and wind patterns. But this is clearly an idealization—the geologic time-scale dynamics will indeed have an impact on the river in some manner, just not one at the scale we are currently modeling.

These heuristics answer both what is idealized and why it is an idealization. Namely, idealizations are those parts of models that elide dynamics, and refer to things or thing-like properties. They are false *because* they refer to these things or thing-like properties. Whenever a model contains aspects that treat the system as fixed, static, determinate, particular, non-contextual, as having a subject, or as continuant, we recognize these descriptions as idealizations to simplify the identification of processes by ignoring or neglecting others.

Processes realism is thereby immune to the worry posed by fictions and falsehoods in scientific models. Processes put in continuity with experimental dynamics are always retained as models are improved, since the fictional elements of the model are about non-processual things. Interestingly, language throughout scientific literature and history supports this. Scientists often remark on which aspects of a system they are "holding fixed," which set of interactions or dynamic considerations they are "treating as negligible," or which contextual factors they are eliding by treating "all things being equal." We should expect that this language is not accidental, that scientists are explicitly recognizing that they are idealizing a system as thing-like.

Moreover, this gives us the first piece of inductive evidence that the process realist can and should reject a lingering assumption in both the metaphysics and realist literatures: that metaphysics should be primarily related to physics, since physics is somehow more fundamental or more real than the systems studied in other sciences. While it is true that the process realist will still take physics just as seriously as will the thing realist, the process realist will also take "higher level" sciences seriously as well. This follows in part from the characterization of different-scale idealizations. Processes are not defined by how they mereologically decompose into definite things, structures, properties, etc. Rather, processes are *identified* by participation in a dynamic context. Two scientific models will simply describe and identify different dynamic contexts by the very nature of their experimental and observational design. No experiment is more fundamental, real, or true than another. Both sets of processes, then, are equally valid as metaphysical posits.

[4.2.2]: Underdetermination, Context, Exploration

In virtue of idealizing, and eliding dynamics both known and unknown, models leave open many aspects of the system for later development. In the Bohr model, the experimentally identified processes—the transitions—are represented such that those identifications can be developed. The model tells us *that* these dynamics exist, contextually identified with the specific electromagnetic interactions amalgamated in the idealization of the orbitals. The model then invites us to investigate these dynamics more directly, and to describe them in more detail. We do this by unpacking our idealizations. We might, for instance, wish to incorporate internal interactions between spin and momentum within atomic systems. In order to do this, we design more complex experiments involving nuclear magnetic resonance and the application of external magnetic fields, in addition to our original interventions of bombarding the atom with electromagnetic energy. When we do this, we see that the transitions grow more complex: we now include fine- and hyperfine-splitting of the orbitals, and so a greater variety of possible transitions.

In this way, we see that the dynamics identified in the model may be described with more experimental detail, greater precision, more integration with other dynamics described in different models, and so on. The original dynamics remain real as we continue to explore and improve our understanding—the original identifications will still be useful and adequate in some experimental contexts—but more precise, nuanced, and complex descriptions become available when needed. In contrast, those aspects of our models that are idealizations—the thing-like parts—are eventually replaced by non-static but stable descriptions. For example, the static Bohr orbits are replaced by energy states that are recognized as merely stable, with the potential to be perturbed and split by dynamic interactions of the system with an external magnetic field.

Models are therefore exploratory precisely because we can always add new dynamic contextual factors into our experiments. Our processual descriptions of these experiments in turn are made more nuanced, i.e., our models are developed as we improve the breadth of the dynamics we consider within them. This allows the process realist to explain why idealizations are essential to the exploratory functions of scientific models (Potochnik 2020).

Underdetermination, then, is merely a recognition of the exploratory character of any model in this way. When we were in the business of positing some definite, unchanging list of ontic particulars—a collection of things, properties, structures, etc.—underdetermination presented us with a problem: these entities do not change, and can admit of no alteration without conceptual annihilation.

However, the mereology of processes, and the soft epistemic pluralism of process realism, resolves this worry. No process contextually isolated and identified is ever false so long as the context is provided without obfuscation. Rather, we seek more nuanced contexts as we explore the world with our scientific models, and so identify new processes within the experimental whole. It remains true that the processes identified by the Bohr model can still be identified: we can always perform the same experiments whereby those processes are contextually identified. Similarly, if two models identify the same experimental dynamics, then their descriptions of the dynamics that fill in the gap between intervention and observation will differ only in the specific idealizations that they posit. Since idealizations are loci for exploratory scientific progress through novel experiments, such competing models will differ not in ontology but in how we might epistemically proceed to improve and refine our ontology, an improvement that is non-destructive to the process interpretation.[35]

[4.2.3]: The PMI, the Processes of History

If models are exploratory in this way, then we recover what Kuhn called the continuous character of scientific progress. Namely, science progresses by the development and improvement of nuances in experimental design, observational method, technologies to enable system isolation and new means of identification of sub-dynamics in these systems, and the improvement of more fine-grained conventions of language for incorporating many models together in communities of discourse. This means we are in a position to consider how the process realist resolves the PMI.

The first response to the PMI follows from our exemplar: the process realist simply provides us with selective tools for identifying which parts of our models are real and which are not. Namely, the identified processes are real *as they are identified within the relevant experimental and observational dynamics*, and the things or thing-like things are not.

This much is standard; every selective realism responds to the PMI in much the same manner.[36] However, the process realist can improve on this in two ways. First, the process realist recharacterizes the myriad examples given in

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[35] See Penn (2023, Ch. 5) for a thorough account of how process realism resolves direct conflicts between models, specifically considering the case of supposedly incompatible nuclear models (c.f. Morrison 2011 for an argument that these models are irreconcilably incompatible).

[36] It should be noted that I do not think that other forms of selective realism are necessarily unsuccessful in this response.

support of the PMI in the literature. Notice that case studies used to support the PMI in the literature almost always refer to thing-like (substance-like, and structure-like) entities. Ptolemaic orbits conceived non-dynamically but structurally as literal celestial spheres. Substances like phlogiston and luminiferous aether meant to provide the substantial medium for their respective thermal and electromagnetic dynamics. Definite properties of internal vitalism or anima, meant to act as particular, continuant sources and vehicles for the motions observed in the life sciences. Even contemporary classical particles, wholesale objects intended to carry all of the properties that, in quantum field theory, are mere measurables and determinables within the field-theoretic interactions.[37] All of these have been rejected, and all because the posits themselves are too thing-like, be they particular, unresponsive to dynamic context, continuant, definite, or even unmeasurable.

This means that the process realist can *co-opt* the PMI: the meta-induction is an induction not that realism is untenable, but rather that the substance paradigm is untenable. The process realist and the antirealist celebrate together the demise of this obstinate obstacle paradigm of objects.

Second, and more interestingly, the process realist can give a reason why we should expect this trend to continue. That is, process realism builds its ontology not on definition and identity criteria, but on identification. This means that its posits are always couched in terms of the processes of experimenters and observers. These, at least, are beyond doubt, except from those who would adopt some form of nihilism or idealism. At no point in the development of this scientific metaphysics are we, and will we ever, be required to infer from or to things, which can only be defined by a priori intuition. No antirealist will ever deny the reality of

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[37] See Malament (1996).

experimental dynamics. No matter when these experiments are performed, they identify similar processes, because the identification *just is* the experiment.[38] In short, process realism is not merely conducive to empiricism, empiricism is the metaphysical method.

Thus, the process realist is not in danger of overcommitting on the metaphysical side of science. However, the intuition underlying the PMI—that the history of science is full of change and evolution—is still very much operative, even in a process realist framework. Science will still involve debates about methods, experimental designs, the correct inferential approach to observation and historical data, the manner in which community values can or should influence the development of our models, about how we process data. Process realism does not resolve these problems simply in virtue of its ontological structure.

But this is good. Process realism embraces the evolution of science. To put it somewhat prosaically, the process realist should exult in the struggle and debate of science, for this is merely the meta-process whereby we improve our identification of physical processes participant in the world. Science is both about processes, and is itself a process.

Thus, the process realist provides both an explanation for the reference- and descriptive-failure of specific aspects of models, and a means to recognize which parts are retainable within our ontology. Namely, we should expect in current and historical models that all parts of those models that are static, substance or thing-like, or otherwise inextricably tied to the metaphysics of the substance paradigm are just those aspects that will eventually be eliminated in the development

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[38] I say "similar," because all processes are radically unique; they lack identity at all, since they are merely *identified.* This is the crucial way in which they differ from things: things can be said to be identical, along the lines of Leibniz's law, or a variant thereof.

of superior (or simply new) models and methods. Thus, the process realist can explain why the PMI is not merely a worry, but a legitimate and principled criticism of certain realist commitments.

[4.3]: Upshots and Constraints on Process Realism

Process realism is largely immune to the traditional worries of antirealists. In fact, the process realist shares these worries, but directs them toward their appropriate target: substance-paradigm forms of realism, or thing realism for short. This gives the process realist incredible power viz a viz its ability to unify much of the exceptional work being done in contemporary philosophy of science. At the same time, the manner in which process realism assuages the worries of the antirealist significantly constrains what the process realist can say about many philosophical issues, both metaphysical and epistemological. I collect an incomplete list here, in lieu of summarizing the preceding discussion, in no particular order.

Idealization (and other fictional elements of models): While no universal account of idealization is evident, the process realist provides a heuristic for idealizations that is extensible and fecund: idealizations are the result of treating the dynamic world as if it is static, in one form or another.

Exploration through models: process realism gives us a means for understanding how exploration, and scientific developments, are to be understood: science develops by steadily eliminating non-scientific (i.e., non-empirical) elements of our models in favor of more nuanced and novel dynamics.

Soft Epistemic Pluralism: Process realism allows that all scientific investigations are equally valuable and reality-tracking, but eliminates the metaphysics (specifically, the thing-like mereology) that would make such a view troubling. Instead, we understand that there is a single world, in which all processes are participants, and classify various identifiable processual parts of the dynamic whole in terms of the nuances in our epistemology of identification.

Fundamentality Constraint: This means that process realism cannot admit of fundamentality talk except as it might be defined purely in terms of the maturity or development of epistemic methods. Even then, process realism cannot admit of any "final science," and can only admit that there is at most one fundamental process: the world as a whole, to its entire and infinitely complex extent.

Identify-Identification Constraint: The process realist cannot make use of identity talk, except as equivocal with talk of identification. That is, the identity of a process is nothing more than the means by which we could identify it through empirical processes. This does not make process realism any less of a metaphysical position, but does mean that our metaphysics and our epistemology are largely, if not entirely, integrated via reflective equilibria.

Only-Experimentally-Identifiable Processes: The process realist cannot commit to *all* processes in scientific models. Instead, the process realist must only commit to those processes that are identified by experimental dynamics. We see this as part of the process interpretation of the Bohr model: both the transitions and the orbiting electrons are prima facie processes identified by the model, and neither is "observable" in the traditional sense of being directly interactive with our unadulterated senses. However, only the transitions are put into sequential and participant dynamic contact with the experiments we actually perform. The "orbiting electrons" could be identifiable by the process described by Bohr—bringing an electron close to a nucleus until it is maximally bound, but they are never put into contact with dynamics that would reach our senses (the dynamics that would do this would be the observed collapse of matter). Therefore, we only commit to the transitions. This constraint is essential for any form of process realism that wishes to consistently and coherently avoid the concerns of the antirealist.

Essentiality of historical analysis: Process realism will always understand the history of science as a continuous, dynamic progenitor of contemporary scientific practices. While we can discuss the novelty of a particular view, we do not understand this in terms of divine conception of new entities. Rather, we understand science along the late Kuhnian terms: "that scientific knowledge can be properly understood only as a product of history, of a temporally and spatially continuous developmental process." (Mladenovic 2022, p. 28). Moreover, the process realist will always encourage philosophical discussion of science to integrate history wherever possible, in order to best understand scientific models within their own, sociological and intellectual dynamic contexts.

The processuality of data: Although left largely undiscussed here, it should be natural enough to suppose that the process realist will require us to think of data as itself processual, rather than particular, structural, or fixed. This, at least, has already been argued elsewhere (Bokulich and Parker 2022). The process realist simply provides a metaphysics wherein the conclusions of Bokulich and Parker are not only acceptable, but necessary.

Explanation Constraint: The process realist must account for explanation not in terms of system-parts, but in terms of participation in dynamic contexts. This is a significant shift in the manner in which philosophers of science have traditionally deployed and discussed the idea of explanation, and I unfortunately cannot discuss it here. However, such a shift in our thinking is largely the result of the reliance on interventionism (or a version thereof), which is a generally accepted advance in the philosophy of scientific epistemology.[39] As such, I will leave this as a promissory note that the process realist can indeed provide an account of explanation that meets this constraint, without sacrificing or otherwise diluting our ability to understand historical and contemporary examples of explanation.

The essentiality of diverse perspectives: Corollary to the fundamentality constraint, the process realist should never exclude good-faith scientific practice and modeling in any capacity. This is because the

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[39] See Woodward (2003, 2014a, b).

process realist cannot prefer one identification of processual participants in the world over another a priori. Preferences that do emerge can only be trusted so long as they were arrived at by discursive and dialectical processes that themselves are open for debate and development. In other words, the process realist should distrust any aspect of science that is kept artificially fixed, static, or imperturbable.

Sense-Perception Constraint: Much like the empiricists throughout the 20th and 21st centuries, the process realist must provide an account of "observables" that can handle cases of observables far removed from our unadulterated senses. E.g., cases in the distant past. This must be done without breaking the necessary continuity of "observational" processes with "external" processes.

Scientific Language Constraint: Perhaps the most significant constraint on process realism is the inability to admit of definite reference. I pointed out contemporary and historical work above that supports the idea that we do not actually need direct reference to have meaningful linguistic and metaphysical accuracy or precision. While I think this is an acceptable constraint, it is still worth mentioning.

[5]: Conclusion, or, Why Past Unifications of Empiricism and Realism have failed.

Several attempts to resolve the tension between realism and antirealism have been made in the past. One of the more recent examples comes from Psillos (2007), who argues that realism can be made compatible with empiricism if we take seriously Schlick's (1932) conflation between the how-we-know something with the what that something is. Essentially, Psillos follows Feigl and Reichenbach in a "Copernican turn," whereby "the observer [is related] to the observed, the indicator to the indicated,—not epistemically,—but so to speak cosmologically" (Feigl 1950, 41). Providing this relation will give the realist a middle ground position to ground their realism without commitment to transcendental reasoning.

Unfortunately, Psillos' approach does not work. A mere relation between observer and observed is not enough: we might imagine that we could provide any number of such relations with equal and empty evidence, all of which might logically succeed but none of which would satisfy. Indeed, so long as we accept that there is metaphysical independence between observed systems and observers, any relation we provide between the two will just amount to transcendental reasoning anyway.

Nevertheless, Psillos—and by extension Feigl, Reichenbach, and Schlick—are correct that the means by which realism and empiricism can be made compatible lies in a strong association of the identity of an entity with its identification. However, we learn from them by contrast that this association cannot be anything less than full-throated. We must reframe the realism debate entirely, and discard the distinctions that objectified the world in favor of non-objective understanding. In essence, we must adopt a process realist framework.

Process realism has a great capacity to unify. Where before scientific metaphysics and scientific epistemology existed in an uneasy truce, process realism makes them allies. Process realism can support, co-opt, and even explain the advances made on idealizations, data processing, scientific historicizing, contextual/structural explanation, community and perspectival virtues, and much more. This means that process realism is not only a means of resolving a perennial debate, but also a fecund research program from which springs untold benefits. The elaboration of these benefits must, for now, remain prospective. However, the promise of process realism is evident, if only as a scientific metaphysics that is, at last, compatible with empiricist epistemology.

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