RELATIONAL REALISM AND THE ONTOGENETIC UNIVERSE

subject, object, and ontological process in quantum mechanics

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Abstract

Amid the wide variety of interpretations of quantum mechanics, the notion of a fully coherent ontological interpretation has seen a promising evolution over the last few decades. Despite this progress, however, the old dualistic categorical constraints of subjectivity and objectivity, correlate with the metrically restricted definition of local and global, have remained largely in place – a reflection of the broader, persistent inheritance of these comfortable strictures throughout the evolution of modern science. If one traces this inheritance back to its ancient roots in Plato and Aristotle, it is clear that the coherence, scientific utility, and historical durability of the various natural philosophies that followed have been directly proportional to their commitment, tacit or explicit, to object-oriented realism. As Simondon might put it, it is a commitment to the primacy of individuated substance over the process of individuation. For Whitehead, it is the misplaced assimilation of becoming to being, of potentiality to actuality. Quantum mechanics has challenged this commitment

with a combined breadth and depth of force that far exceeds any other theory in the history of science. The theory's objectively demonstrable empirical application is manifest only by way of a fundamentally subjective, context-dependent mechanism of measurement. More compelling still, actual system states are always *actualizations* of locally contextualized yet globally conditioned *potential* system states, such that "globally objective" reality is no longer merely the object of local measurement, but also its product. Thus, any coherent, ontological interpretation of quantum theory must include a conceptual framework by which objectivity and subjectivity, actuality and potentiality, global and local, being and becoming, individuated fact and process of individuation, are no longer understood as merely epistemic, mutually exclusive category pairs descriptive of an already extant, closed reality – but rather as mutually implicative ontological categories explicative of an ontogenetic, open reality-in-process.

> The term "*ontogenesis*" receives its full sense if, instead of giving it the restricted and derived meaning of the genesis of the individual […] one uses it to designate the character of *becoming of being*, that by which being becomes, insofar as it is, as being. The opposition between being and becoming can only be valid within a certain doctrine that supposes that the very model of being is a substance. (Gilbert Simondon 5–6)

> The actual world is a process, and that process is the becoming of actual entities […] In the becoming of an actual entity, the *potential* unity of many entities in disjunctive diversity […] acquires the *real* unity of the one actual entity; so that the actual entity is the real concrescence of many potentials […] In other words, it belongs to the nature of a "being" that it is a potential for every "becoming." (Alfred North Whitehead, *Process and Reality* 22)

In both Simondon's concept of ontogenesis and the Whiteheadian, relational realist interpretation of quantum mechanics,[1] the term "global" refers to a synthetic process of collective individuation. It is an unfolding totality driven via locally contextualized potential predicative relations wherein every quantum individuation – every quantum unit of relation (i.e., every quantum measurement event) – is properly understood as an actualized potential relation that is at once “subjectively” *contextualized locally* and “objectively” *constitutive globally*. Thus, both Simondon’s ontogenetic universe and the relational realist interpretation of quantum mechanics depict the mutual implication of local/subjective and global/objective in terms of locally contextualized *actualized facts* (Simondon’s “individuated” facts) and their globally extensive *potential relations* (his “preindividuated,” potential facts). Both frameworks are “ontogenetic” in the sense that the process of individuation – the novel actualization of potential relations – generates novel actual facts that, in turn, lead to novel potential relations, yielding additional novel actual facts, and so on.

Fundamentally, then, the ontogenetic universe entails two mutually implicative ontological categories: “individuated” actualities and “preindividuated” potential actualities in a mutually implicative and mutually synthetic relationship. Each category yields its own distinctive portrait of the world and its own modality of experience; more important, the mutually implicative and mutually synthetic relationship of these categories obviates the possibility of reductively assimilating one portrait to the other. The category of individuated actualities evokes the *individuated-contextual-actual* portrait of ontogenesis – the global as an objective totality of locally contextualized dative facts – namely facts whose local spatiotemporal contextualization allows for their coherent relation both causally and logically. The category of preindividuated potential actualities evokes the *preindividuated-precontextual-potential* portrait of ontogenesis – the domain of pure, precontextualized potential relations among facts – i.e., those aspects of potential relations that exceed local contextualization within the process of individuation.

> Individuation must therefore be considered as a partial and relative resolution that occurs in a system that contains potentials and encloses a certain *incompatibility in relation to itself* – an incompatibility made of forces of tension as well as of the impossibility of an interaction between the extreme terms of the dimensions. (Simondon 5)

Likewise, for Whitehead, the category of “Pure Potentials for the Specific Determination of Fact, or Forms of Definiteness” (*Process and Reality* 22) are always “potentialities *for* actual entities.” Every pure potential is “precontextual” in that it “is neutral as to the fact of its physical ingression in any particular actual entity of the temporal world” (44). In quantum mechanics this “pure potentiality” in the category of the *preindividuated-precontextual-potential* is reflected in the fact that the global state vector $|\psi\rangle$ in the equation –

$$|\psi\rangle = \alpha_{ijk} \sum_{i,j,k} |s\rangle_i |d\rangle_j |e\rangle_k$$

where $|s\rangle$ represents a locally contextualized system state, $|d\rangle$ represents the state of the related locally contextualizing measurement basis, and $|e\rangle$ represents the state of the unmeasured environment – can be expressed as the sum of an indefinite number of potential states or "potentialities of definiteness," referent to no specific actualities and potentially referent to all. Many of these potential states are incapable of integration, forming nonsensical, interfering superpositions, reflective of Simondon's characterization of the *preindividuated-precontextual-potential* as enclosing "a certain *incompatibility in relation to itself* – an incompatibility made of forces of tension as well as of the impossibility of an interaction between the extreme terms of the dimensions" (5).

A binocular view of these two portraits together, the *preindividuated-precontextual-potential* and the *individuated-contextual-actual*, yields a third portrait – a view of the global as a unified, nonlocally restricted, relational structure (a "transductive" structure in Simondon's terminology) – the *transductive-transcontextual-relational* portrait of the universe. Together, these three portraits evoke a fundamental depiction of the universe as an ontogenetic network of actualizations of potential relations constitutive of a global process of emergent unfolding.

Each of these three philosophical portraits finds its reflection in the Whiteheadian, relational realist interpretation of quantum mechanics, which mathematically formalizes the connective structure by which the distinctive features of each portrait can be coherently interrelated. For example, the *individuated-contextual-actual* portrait is exemplified quantum mechanically as a *locally contextualized measurement outcome state*, i.e., a locally contextualized evaluation of a physical observable, such that the local contextualization is representable as a Boolean subalgebra. The *preindividuated-precontextual-potential* portrait is exemplified quantum mechanically by the fact that potential relations among observables always exceed the constraints of any *particular* local measurement context/Boolean subalgebra, and more important, even exceed the constraints of the global totality of all particular local contexts together (namely the Kochen–Specker theorem[2]). In quantum mechanics every measurement event – every individuated actualization of a potential quantum state – is locally contextualized via an orthonormal measurement basis/Boolean subalgebra whereby potential measurement outcomes are expressible as mutually exclusive and exhaustive, probability-valuated, either-or propositions. Every such locally contextualized measurement is always understood as “non-maximal” because there will always be potential evaluations that exceed not only that particular local contextualization, but the totality of all local contextualizations. There is, in other words, no “global Boolean algebra” in quantum mechanics that can be taken to represent the totality of all locally contextualized potential states. This idea finds its analog in Simondon’s concept of ontogenesis:

> It is possible to put forward the hypothesis, which is analogous to that of the quanta in physics and also to that of the relativity of potential energy levels, that individuation *does not exhaust all of the preindividual reality* […] A certain level of potential remains, and further individuations are still possible. (8)

The phenomenon of nonlocal quantum entanglement in composite quantum systems well exemplifies this idea. In such systems, locally contextualized regions of the composite system are spacelike separated and therefore nonlocal relative to one another (i.e., mutually causally irrelevant). Nevertheless, measurement of such systems reveals a nonlocal “transductive” overlapping of the constituent local measurement contexts, such that correlations between the restricted set of potential measurement outcomes (“individuations”) defined by the local contexts individually are exceeded. This nonlocal overlapping is formalized mathematically via a topological overlapping of the Boolean subalgebras representing the local contexts in relation. This is the *transductive-transcontextual-relational* dimension of ontogenesis, evinced quantum mechanically by the fact of nonlocal correlations among locally contextualized measurements – i.e., correlations among measurement outcomes that exceed the spatiotemporal restrictions of their individual local contextualizations. The phenomenon of nonlocal probability conditionalization (an example of Simondon’s “transduction”) in EPR-type experiments – a signature feature of quantum mechanics which will be discussed in greater detail presently – is perhaps the most conventional exemplification of the transductive-global-relational portrait of ontogenesis in modern physics.

> By transduction we mean an operation – physical, biological, mental, social – by which an activity propagates itself from one element to the next, within a given domain, and founds this propagation on a structuration of the domain that is realized from place to place: each area of the constituted structure serves as the principle and the model for the next area, as a primer for its constitution, to the extent that the modification expands progressively at the same time as the structuring operation. (Simondon 11)

When one considers nonlocal quantum mechanical correlations via either Simondon's concept of transduction or the Whiteheadian, relational realist interpretation of quantum mechanics, one finds these correlations are ultimately grounded in a mutually implicative relationship between local and global. This relationship has only two possible modes, jointly operative in every quantum measurement event (Epperson and Zafiris 54–57, 186–94, 217–18, 229–34):

1. *Extension of the local to the global*, wherein locally contextualized individuations/actualized measurement outcomes (i.e., the *individuated-contextual-actual* portrait) condition global potentia (i.e., the *preindividuated-precontextual-potential* portrait) via a fundamentally nonlocal, non-metrical, non-spatiotemporally restricted, global relational structure (i.e., the structure of the *transductive-transcontextual-relational* portrait) by which the global unfolds as a synthetic process. This is evinced, as mentioned above, by nonlocal probability conditionalization in quantum mechanics, whereby locally contextualized individuations/actualized measurement outcomes, when extended relationally to the global state, synthetically *augment* the global state, such that the latter is properly understood not as a static totality, but rather as an emergent, unfolding totality.

2. *Restriction of the local by the global*, wherein global individuations (actualized quantum states) condition local potentia and their local contextualization. This is evinced, for example via the phenomenon of environmental decoherence in quantum mechanics.

Thus, the bidirectionally conditional mutual implication of local contextuality and global objectivity in quantum mechanics is exemplified by the concurrence of [1] the *extension* of locally contextualized *actual* measurement outcomes *to* the global quantum state, and [2] the *restriction* of local contextualization of *potential* measurement outcomes *by* the global quantum state. In the relational realist interpretation of quantum mechanics, this bidirectional conditioning is formalized mathematically via the category theoretic concept of adjunction (Epperson and Zafiris 229–32, 273–76, 328–30) – a particularly powerful innovation in that it is uniquely suited to the local–global topological relations of quantum measurement contexts discussed above.

The central conceptual challenge, then, for any ontogenetic interpretation of quantum mechanics and its practical, empirical application is not only the problem of measurement (i.e., the problem of actualization of potentia – the problem of the existence of a unique actual measurement outcome when quantum mechanics terminates in a matrix of probability-valuated potential outcomes) – nor is it merely the problem of local subjective measurement contextualization having global objective significance; the central challenge underlying both of these problems, rather, is properly understanding, via a coherent and empirically adequate conceptual scheme, the mutually implicative relationship between local and global in quantum mechanics. This necessarily entails the construction of a formal philosophical and mathematical framework that adequately depicts how the *logical* features of this relationship can be shown to condition the *causal* features in a way that yields the nonlocal, transcontextual correlations ("transductions") discussed above. Further, the framework would need to depict what Simondon calls the "metastability" underlying not only these correlations, but also underlying the process of the actualization of potential measurement outcomes in general.

These desiderata are all central features of the relational realist interpretation of quantum mechanics and the ontogenetic universe it portrays. Its connection with Simondon's concept of ontogenesis is most clearly illustrated by focusing on the relationship between:

[a] the *individuated-contextual-actual* portrait

correlated with

local-metrical-coordinate spacetime structure

and

[b] the *transductive-transcontextual-relational* portrait

correlated with

global-mereotopological-genetic quantum event structure

As introduced above, the *individuated-contextual-actual* portrait of ontogenesis depicts the global as a totality of locally contextualized dative ("individuated") facts – namely quantum events – whose local spatiotemporal contextualization allows for their coherent relation both causally and logically. In the relational realist framework, this causal-logical order has its basis in the Whiteheadian notion of an objective mereological ordering (a mereotopological ordering in the relational realist interpretation) of fundamental relational events (i.e., quantum events as Whiteheadian "actual occasions"). Crucially, this objective global *mereotopological* ordering of quantum events must not be misconstrued as an objective global *spatiotemporal* ordering. While the *individuated-contextual-actual* portrait of ontogenesis is compatible with an ordering structure of linear-sequential time (i.e., local spacetime), in the relational realist interpretation of quantum mechanics, local temporality, and indeed all *metrically* extensive relations, constitute a higher-order reflection of a fundamentally *mereotopological* extensive structure. This structure is grounded in the concept of histories of quantum events,[3] with each event bijectively related to its local contextualization. Here, "local" does not refer to metrically extensive (relativistic) locality, but rather to the idea, introduced earlier, that each quantum measurement context is representable as a particular Boolean algebra. Locality, in other words, is fundamentally defined topologically, not metrically.

Likewise, for Simondon, the spatiotemporal ordering of individuals presupposes the transductive, ordering operation of individuation. Returning to the previous quote:

> By transduction we mean an operation – physical, biological, mental, social – by which an activity propagates itself from one element to the next, within a given domain, and founds this propagation on a structuration of the domain that is realized from place to place: each area of the constituted structure serves as the principle and the model for the next area, as a primer for its constitution, to the extent that the modification expands progressively at the same time as the structuring operation. (Simondon 11)

As an ordering structure, the concept of transduction can be correlated with the Whiteheadian, relational realist concept of a quantum event structure – a mereotopological supersession of *internally related* [4] quantum events that includes, bijectively, a mereotopological supersession of the events' local Boolean measurement contexts. In this way, the serialized internal relation of each locally contextualized quantum event/individuation to its dative global environment can be correlated with the serial-inclusive mereotopological relatedness defining the fundamental extensiveness of the universe, with each concrescent integration of the whole internally related to the totality of logically mereotopologically prior integrations (i.e., prior in sequence, not prior in time).

It should be noted, however, that for Simondon, transductive internal relations of this kind are characteristic of "living individuals" only, not "physical individuals."

> The physical individual, perpetually de-centered, perpetually peripheral to itself, active at the limit of its domain, *does not have a veritable interiority*; the living individual, on the contrary, does have a veritable interiority because individuation carries itself out within the individual; the *interior is also constitutive* in the living individual, whereas in the physical individual, only the limit is constitutive, and *that which is topologically interior is genetically anterior*. The living individual is contemporary to itself in all of its elements, which is not the case for the physical individual, which carries something of the past that is radically past, even when it is still growing. (Simondon 7–8)

If one generalizes the complexity of individuation and transduction in Simondon's category of living systems to his category of physical systems per the Whiteheadian approach, where the more complex internal relations constitutive of higher-order (e.g., "living") systems exhibit the same categorical structure as less complex, lower-order (e.g., merely "physical") systems – thus differing not categorically but only in degree of relational complexity – one finds that in both relational realist quantum mechanics and in Simondon's concept of ontogenesis, individuation and transduction entail a rich and highly complex internal relational structure with both extensive and intensive dimensions. One dimension is the local, relativistically restricted mode of spatiotemporal causal relation of the individuated-contextual-actual portrait of ontogenesis. This spatiotemporal-extensive *coordinate structure of individuals* when extended to transduction, however, presupposes an underlying global logical (mereotopological) *genetic structure of individuations*.

> Transduction corresponds to this existence of relations that are born when the preindividual being individuates itself; it expresses individuation and allows it to be thought; it is therefore a notion that is both metaphysical and *logical*. It applies to ontogenesis, and is ontogenesis itself. (Simondon 11)

This, again, is the *transductive-transcontextual-relational* dimension of ontogenesis. In relational realist quantum mechanics, the global, logical-mereotopological quantum event structure – the *genetically intensive structure of individuations* – is the basis for the relativistic causal structure – the *coordinately extensive structure of individuals*. And as discussed above, the global mereotopological structure is a fundamentally asymmetrical, serially ordered global structure of internal relations. In relational realist quantum mechanics, in other words, the logical-mereotopological order, not the metrical spatiotemporal order, is the fundamental order of the extensive continuum. In the words of Whitehead:

> The extensive continuum is a complex of entities united by the various allied relationships of whole to part, and of overlapping so as to possess common parts, and of contact, and of other relationships derived from these primary relationships […] *It is the first determination of order* […] The properties of this continuum are very few and *do not include the relationships of metrical geometry*. (*Process and Reality* 66)

> *These extensive relationships are more fundamental than their more special spatial and temporal relationships* […] Extension, *apart from its spatialization and temporalization*, is that general scheme of relationships providing the capacity that many objects can be welded into the real unity of one experience. (*Process and Reality* 67)

Whitehead's conception of the fundamental, non-spatiotemporal, mereological order of the extensive continuum and its unifying role within his cosmological scheme is thus central to the mereotopological order formalized in relational realist quantum mechanics, and the role played by this order in the *transductive-transcontextual-relational* portrait of ontogenesis. And as has been well-demonstrated in physics, without a single exception to date, any deduction from that fundamental logical-mereotopological order to a more special order, such as the causal order of relativistic spatiotemporal extensiveness, always maintains commitment to the fundamental, internal relational, logical-mereotopological order. But equally well-demonstrated in physics, commitment to this order never entails sheer reduction to it. As discussed earlier, the global, transductive, mereotopological quantum event structure is itself an inherently non-reductive, synthetic structure; it cannot be reduced to a single classical logic – i.e., a global Boolean algebra. Likewise, for Simondon,

> Classical logic cannot be used to think the individuation, because it requires that the operation of individuation be thought using concepts and relationships between concepts that only apply to the results of the operation of individuation, considered in a partial manner. From the use of this method, which considers the law of identity and the law of the excluded middle as too restrictive, a new notion emerges that possesses a multitude of aspects and domains of application: that of *transduction*. (Simondon 10–11)

While transduction across multiple individuations cannot be reduced to the classical logical relations defined by the context of any single component individuation – i.e., the laws of identity, excluded middle, and non-contradiction as defined by that individual local context – transduction does entail a transcontextualization *across* these component individuations. Thus, transcontextualization presupposes some degree of compatibility with respect to these contexts.

In relational realist quantum mechanics, the asymmetrical internal relation among local quantum measurement contexts, combined with the presupposition that individual local measurement contexts are always structurally Boolean, together constitute the *compatibility condition for logical causality* in quantum mechanics (Epperson and Zafiris 58–63, 148–56). Here, "logical causality" refers to the necessary presupposition in modern physics of the universal, categorical correlation of [a] the asymmetrical order of material implication and logical consequence with [b] the asymmetrical order of causal relation – i.e., the correlation of *if* → *then* with *cause* → *effect* (Epperson 80–83; Epperson and Zafiris 139–78). Thus, logical causality is fundamentally about the process of relational individuation, not relations of individuals. Likewise, for Simondon,

> If it were true that logic provided statements about being only after individuation, it would be necessary to institute a theory of being that is anterior to any form of logic; this theory could serve as the foundation to logic, because nothing proves in advance that there is only one possible way of individuating being. If multiple types of individuation were to exist, multiple logics would also have to exist, each corresponding to a specific type of individuation. The classification of the ontogeneses would allow us to *pluralize logic* using a valid foundation of plurality. (13)

Relational realist quantum mechanics does precisely this in its own depiction of ontogenesis. The compatibility condition[5] is formalized as a sheaf-theoretic mereotopological description of the local–global relation of Boolean algebras – specifically, as a transition morphism from one local Boolean context to another, generating asymmetrical logical and mereotopological revisions of equivalence classes of local contextual Boolean algebras.

Topologically, these revisions yield partial compatibility on their overlapping regions (e.g., partial Boolean compatibility of coarse-grained position and momentum observables, up to the limit of the Heisenberg uncertainty relations). This "inductive limit" (Epperson and Zafiris 156–58, 207, 226–28, 270–307) by which local compatible families of Boolean algebras can be extended globally, is constructed via the formation of a set of equivalence classes of partially compatible Boolean subalgebras, representing partially compatible Boolean contextualized observables, on *all* possible overlaps. The compatibility condition thus requires as a categorical presupposition that all local measurement contexts are structurally Boolean, and that the asymmetrical Boolean structure of any local context is preserved when extended globally, via internal relation, to other contexts (156).

The compatibility condition is thus built upon two foundational concepts:

1. *Locally*, every measurement context must be Boolean, such that in the mixed state, Boolean material implication holds – e.g., for any measurement context *A* it will always be the case that for potential outcomes a_1 and a_2, $a_1 \rightarrow \neg a_2$ ("if a_1, then not a_2") and $a_2 \rightarrow \neg a_1$. This, of course, is just the law of non-contradiction for an observable a with only two possible eigenstates (i.e., potential outcome states) a_1 and a_2. This number, however, has no upper limit in quantum mechanics.

2. *Globally* (i.e., when local contexts are brought into nonlocal relation), intra-contextual Boolean material implication (that is, *within* individual local measurement contexts) must be relatable transcontextually, *across* these local contexts (i.e., "globally"). As discussed earlier, the structure of relations among the totality of quantum events is non-Boolean, evinced by both the non-commutativity of quantum observables, and because the laws of non-contradiction and excluded middle cannot be shown to hold globally in quantum mechanics. That is, one can never, even in principle, evaluate the totality of quantum observables as a comprehensive scheme of mutually exclusive and exhaustive true/false propositions.

However, this *can* be done within local Boolean contextualizations of this global structure; that is, local Boolean sectors of the non-Boolean global lattice can be defined. In this sense, the global quantum event structure, even though it cannot be fully embedded within a global Boolean algebra, can be represented via a partial Boolean algebra – again, so long as one categorically presupposes that all local measurement contexts are structurally Boolean (i.e., representable as a Boolean subalgebra, or as an equivalence class of such subalgebras).

This presupposition is central to the relational realist interpretation of quantum mechanics, which defines the transcontextual structure by which Boolean local–global relations (cf. Simondon's "transductions") can be specified. For even though the totality of facts contained in the global quantum lattice can never be defined completely via deductive analysis, it can be defined approximately via induction from the overlaps of a sufficiently large number of equivalence classes of compatible, or partially compatible, local Boolean subalgebras. It is via this structure that global quantum events can be shown to logically condition local potential measurement contextualization – i.e., *restriction of the local by the global* discussed earlier; likewise, it is via this structure that locally contextualized quantum events can be shown to condition global potentia – i.e., *extension of the local to the global*. Formally, the structure of these overlaps is not fundamentally metrically extensive, and therefore not an implicit feature of the *individuated-contextual-actual* dimension of ontogenesis; rather, it is a *mereotopologically* extensive feature of the *transductive-transcontextual-relational* dimension of ontogenesis.

With respect to relational realism's commitment to a global (but only locally definable) mereotopological order – a crucial question is: do the presupposed topological axioms, definitions, and assumptions given in relational realism (Epperson and Zafiris 261–353) provide sufficient justification for the order they yield? They are first principles of causal relation that correlate, by mutual implication, with the first principles of logical (mereotopological) implication; as first principles, there is thus no deeper principle by which to account for the correlation itself. One could argue that for any physically significant philosophical framework, there must be some additional specified dynamical process that would yield the sought-after correlation in the language of physics. But ultimately this is akin to Plato's exploration of the question, "Why is the universe reasonable?" His own cosmology in the *Timaeus*, like Whitehead's, contains similarly presupposed first principles – along with an insuperable argument in the *Theaetetus* that attempting to apply a physical reductionist argument to account for cosmological first principles will always lead to nothing – literally, to no thing.

As discussed earlier, this correlation of causal relation and logical-mereotopological implication in the *transductive-transcontextual-relational* dimension of ontogenesis is perhaps best exemplified via the phenomenon of quantum nonlocality in measurements of spacelike separated components of a composite quantum system. EPR-type systems[6] are the most widely recognized systems of this kind, where local measurement contexts *A* and *B* – i.e., detectors *A* and *B* – are spatially well-separated, each measuring a different component of the composite system. Because of their spacelike separation, it is assumed that given the relativistic speed of light limitation, the order of component measurement (*A* then *B*, or *B* then *A*) should be irrelevant, since any physical causal correlations between components would require a faster-than-light propagation of energy between *A* and *B*.

What these experiments reveal is that while there is, indeed, no measurable nonlocal, efficient causal influence between *A* and *B*, there *is* a measurable, nonlocal probability conditionalization between *A* and *B* that always takes the form of an asymmetrical internal relation. For example, as discussed above, if *A* registers first, the outcome at *B* is internally related to the outcome at *A*, inducing a probability conditionalization of the *potential* (Simondon's "preindividuated") outcomes at *B* by the *actual* ("individuated") outcome at *A*; specifically, the integration of *B*'s contextualized potential outcomes, represented as an equivalence class of Boolean subalgebras, is "revised"[7] by the actual outcome at *A*. This "transductive" revision, indicative of the asymmetrical internal relation of *B*'s outcome to *A*'s outcome, has been well-demonstrated in countless EPR-type experimental investigations of quantum nonlocality.

While some interpretations resort to exotic explanations such as superluminal propagations of hidden energy or other efficient causal, physical-dynamical mechanisms, the phenomenon of quantum nonlocality can instead be understood intuitively as a logical (mereotopological) conditioning of causal relations – a conditioning implicit in the logical relational structure presupposed by all scientific theories, and rendered explicit in the Whiteheadian, relational realist interpretation of quantum mechanics. Specifically, the mereotopological conditioning of causal relations, defined earlier as the "compatibility condition for logical causality in quantum mechanics," renders explicit the implicit presupposition of: [1] the Boolean internal relational structure of each local context *A* and *B* (again, locally Boolean measurement contexts being a necessary presupposition of the scientific method in general); and [2] the logically coherent global relation of locally contextualized measurement outcomes[8] via a fundamentally logical-mereotopological quantum event structure.

From this perspective, in summary of the present example, the equivalence class of Boolean subalgebras representing the integration of potential outcomes at *B* is "transduced" in Simondon's language – i.e., ontologically revised – by the measurement outcome at *A*, thus exhibiting *B*'s internal relationship to *A*, even when *A* and *B* are spacelike separated. This nonlocal revision entails no propagation of energy of any kind from *A* to *B* and is thus not properly understood as an efficient causal influence of the actualized outcome at *B* by that of *A*; rather, it is a "logical conditioning" (namely a nonlocal probability conditionalization) of the contextualization of the *potential* ("preindividuated") outcomes at *B* via the internal relation of these potential outcomes to the *actualized* ("individuated") outcome at *A*.

The advantage of the topological, category-sheaf theoretic formalism of the relational realist interpretation of quantum mechanics is that it explicitly reveals the formal mereotopological ("transductive") structure by which these nonlocal internal relations are integrated ontogenetically. This type of predication has no classical analog, and no classical analog should be expected in fundamental physics since quantum mechanical potentiality ("preindividual reality") has essentially broadened the concept of a measurement event as an actualized potential outcome state ("individuated actuality").[9]

In this way, writes Simondon, one grasps "ontogenesis in the entire progression of its reality, and [knows] *the individual through the individuation, rather than the individuation through the individual*."

> The search for the principle of individuation must be reversed, by considering as primordial the operation of individuation from which the individual comes to exist and of which its characteristics reflect the development, the regime and finally the modalities. The individual would then be grasped as a *relative reality*, a certain phase of being that supposes a preindividual reality, and that, even after individuation, does not exist on its own, because individuation does not exhaust with one stroke the potentials of preindividual reality. (Simondon 5)

In further exploration of how the mereotopological-intensive *transductive-transcontextual-relational* structure of "becoming" pertains to the metrical-extensive coordinate structure of *individuated-contextual-actual* "beings" in the relational realist interpretation of quantum mechanics, it is useful to examine Whitehead's theory of extensive connection (*Process and Reality* 283–336) – a description of the mereological, logically governed relations subsumed by the concept of a serial supersession of quantum event actualizations ("concrescences") – i.e., a quantum event history. In Whitehead's Theory of Prehensions each concrescing occasion (each "individuation in process") is internally related to the world-as-history, "*each creature including in itself the whole of history*" (*Process and Reality* 228). In his Theory of Extension, Whitehead precisely describes the meaning of the words "including in itself" in that quote: it is defined as a logically governed, serial-inclusive, internal relational, mereological order of whole to part. This order is intended to give *extensive meaning* to the *intensive notion* of a concrescing occasion, in the process of its own individuation, as internally related to the history of the world.

Likewise, for Simondon, "that which the individuation makes appear is not only the individual, but also the pair individual-environment" (5). Thus, both Simondon's concept of ontogenesis and the Whiteheadian, relational realist interpretation of quantum mechanics entail a relational/relativistic notion of "coming into beingness" in terms of [a] the spatiotemporally extensive local contexts of actual occasions in the process of individuation/concrescence, in relation to [b] the spatiotemporally coordinated global environment defined via these local contexts. But again, as evinced by the phenomenon of quantum nonlocality discussed earlier, this relativistic spatiotemporal extensive structure of individuals in no way trumps the logical-mereotopological-intensive structure of individuation and transduction.

With respect to the quantum mechanical exemplification of Simondon's concept of transduction discussed earlier and its necessary presupposition of the "compatibility condition" at the level of the mereotopological *transductive-transcontextual-relational* structure of ontogenesis, there is an analogous presupposition at the level of the *individuated-contextual-actual* structure of ontogenesis: the a priori congruence definition presupposed by relativistic depictions of spatiotemporal extension (Whitehead, *Process and Reality* 331–32). Whitehead writes, for example, "The transformations into an indefinite variety of coordinates to which the 'tensor theory' refers, *all presuppose one congruence definition*. The invariance of the Einsteinian 'ds' expresses this fact" (*Process and Reality* 98). This congruence definition is ultimately anchored in the constancy of the speed of light – although as I noted in *Quantum Mechanics and the Philosophy of Alfred North Whitehead*,

> it should be emphasized that for Whitehead (and likely as well for Einstein) the critical importance of the constant *c* had little to do with its relation to the phenomenon of *light per se*; its significance, rather, lay in the derivative invariance of spacetime intervals and the associated possibility of (i) the asymmetrical, logical and causal ordering of events within spacetime reference frames, and (ii) the provision of a congruence relation that allows for the comparison of spatial and temporal extensive coordinations across diverse spacetime reference frames. (Epperson 177)

Whitehead writes:

> The critical velocity *c* which occurs in these formulae has now no connexion whatever with light or with any other fact of the physical field (in distinction from the extensional structure of events). It simply marks the fact that our congruence determination embraces both times and spaces in one universal system, and therefore if two arbitrary units are chosen, one for all spaces and one for all times, their ratio will be a velocity which is a fundamental property of nature expressing the fact that times and spaces are really comparable. (*The Concept of Nature* 193)

It is thus a cornerstone of both Simondon's concept of ontogenesis and the relational realist interpretation of quantum mechanics that these two structural levels of ontogenesis – the genetic level of mereotopological *transductive-transcontextual-relational* structure, and the coordinate level of *individuated-contextual-actual* structure (namely relativistic spatiotemporal order) – are inherently compatible. Empirical exemplifications of this fact, seen at deeper and deeper levels in the physical sciences, continue to accrue, including explorations of relational realist quantum mechanics and its particular solution to the infamous problem of reconciling quantum theory and general relativity.[10] One of the central implications of these explorations is that the fundamental mereotopological structure of relational realist quantum mechanics provides an empirically sound theoretical framework that accounts for the ad hoc presuppositions and boundary conditions of relativity theory by which the latter's congruence relations are defined. These include the theory's presupposition of set theoretic partial ordering, without which the general theory of relativity would inaccurately portray the universe as a patchwork of causally unrelatable and logically incoherent extensive regions.

In summary, the *transductive-transcontextual-relational* structure of relational realist quantum mechanics depicts the universe as a globally coherent, ontogenetic process of locally contextualized, synthetic, internal relational individuations. In the words of Whitehead:

> The many become one and are increased by one. In their natures, entities are disjunctively "many" in process of passage to conjunctive unity […] Thus the production of "novel togetherness" is the ultimate notion embodied in the term "concrescence" [cf. "individuation"]. (*Process and Reality* 21)

> The atomic actual entities individually express the genetic unity of the universe. The world expands through recurrent unifications of itself, each by the addition of itself, automatically recreating the multiplicity anew […] The atomic unity of the world, expressed by a multiplicity of atoms, is now replaced by the solidarity of the extensive continuum. This solidarity embraces not only the coordinate divisions within each atomic actuality, *but also exhibits the coordinate divisions of all atomic actualities from each other in one scheme of relationship*. (*Process and Reality* 286)

Likewise, with respect to Simondon's concept of ontogenesis:

> Individuation in the form of the collective turns the individual into a group individual, linked to the *group* by the preindividual reality that it carries inside itself and that, when united with the preindividual [potential] realities of other individuals, *individuates itself into a collective unity*. (8)

In relational realist quantum mechanics, the key to the coherence of this "one scheme of relationship" and its "individuation into collective unity" described by Whitehead and Simondon in these passages is its mereotopological framework of structure-preserving, ontological internal relations.

> The basis of the collective reality is already partially contained in the individual, in the form of the preindividual reality that remains linked to the individuated reality; that which we generally consider to be a *relation*, because of the mistaken hypothesis of the substantialization of individual reality, is in fact a dimension of the individuation through which the individual becomes. The relation – to the world and to the collective – is a *dimension of individuation* in which the individual participates starting from the *preindividual reality* that individuates itself step by step. (Simondon 8–9)

This dimension of individuation is the *transductive-transcontextual-relational* dimension of universal ontogenesis. Its exemplification in modern physics, formalized via the serial-mereotopological framework of relational realist quantum mechanics, is grounded in the internal relatedness of each quantum event to the perpetually unfolding, synthetic global totality of all quantum events as each is actualized/individuated. It is by this process that

> the oneness of the universe, and the oneness of each element in the universe, repeat themselves to the crack of doom in the creative advance from creature to creature, each creature including in itself the whole of history and exemplifying the self-identity of things and their mutual diversities. (Whitehead, *Process and Reality* 228)

notes

1 See Epperson and Zafiris.

2 See Kochen and Specker 59–87.

3 See, for example, Omnès, “Consistent Interpretations”; *The Interpretation* and Griffiths.

4 See, for example, Moore 40–62; Epperson and Zafiris 52–54, 231–36.

5 The compatibility condition in relational realist quantum mechanics can be thought of as a supplement to the Griffiths “consistency condition” (119–27).

6 See Aspect, Dalibard, and Roger.

7 See Bub, “Quantum Logic”; “The Problem of Properties.”

8 See, for example, Omnès, *The Interpretation* 163:

Rule 4: Any description of the properties of an isolated physical system must consist of propositions belonging together to a *common consistent logic*. Any reasoning to be drawn from the consideration of these properties should be the result of a valid implication or of a chain of implications in this common logic

and his No-Contradiction Theorem (162). See, also, in this same volume, chapter 5: “The Logical Framework of Quantum Mechanics” (144–200).

9 For more on the ontological significance of quantum potential states, and the dipolar relation of actual and potential states in quantum mechanics, see Epperson; Epperson and Zafiris 29–102, 139–78; and Kastner, Kauffman, and Epperson 158–72.

10 See Epperson and Zafiris 376–88; see also Zafiris and Mallios 1–14.

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